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Katta et al.

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- (54) **ELECTROMIGRATION-AWARE LAYOUT GENERATION**
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G06F 17/50 (2006.01)
- (52) **U.S. Cl.**
CPC **G06F 17/5081** (2013.01); **G06F 17/5031** (2013.01); **G06F 17/5072** (2013.01); **G06F 17/5077** (2013.01); **G06F 17/5068** (2013.01)
- (58) **Field of Classification Search**
None
See application file for complete search history.

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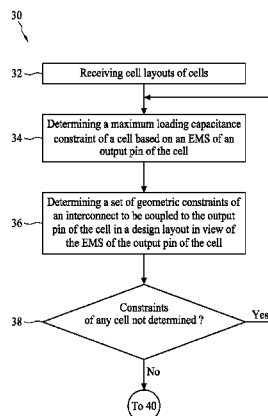
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(57) **ABSTRACT**

In some embodiments, in a method, cell layouts of a plurality of cells are received. For each cell, a respective constraint that affects a geometry of an interconnect to be coupled to an output pin of the cell in a design layout is determined based on a geometry of the output pin of the cell in the cell layout.

20 Claims, 21 Drawing Sheets



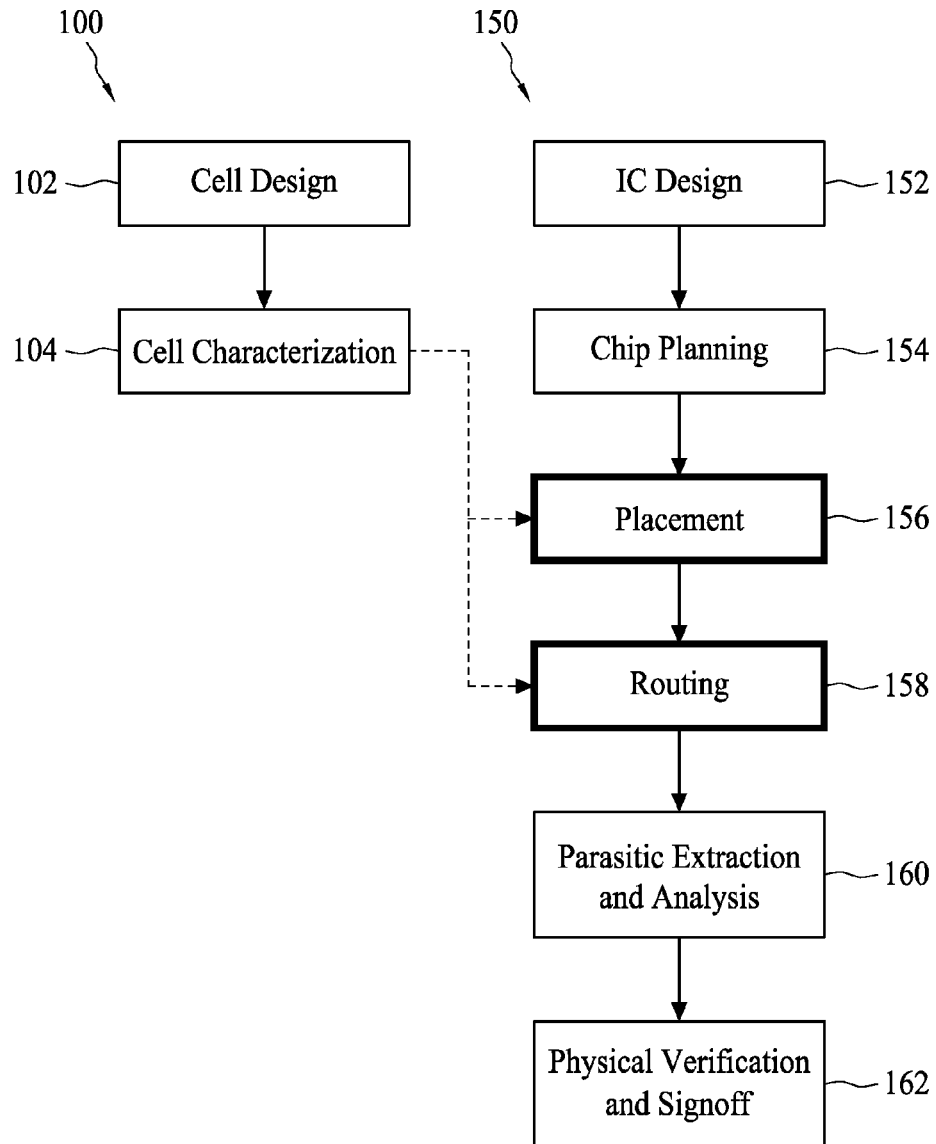


FIG. 1

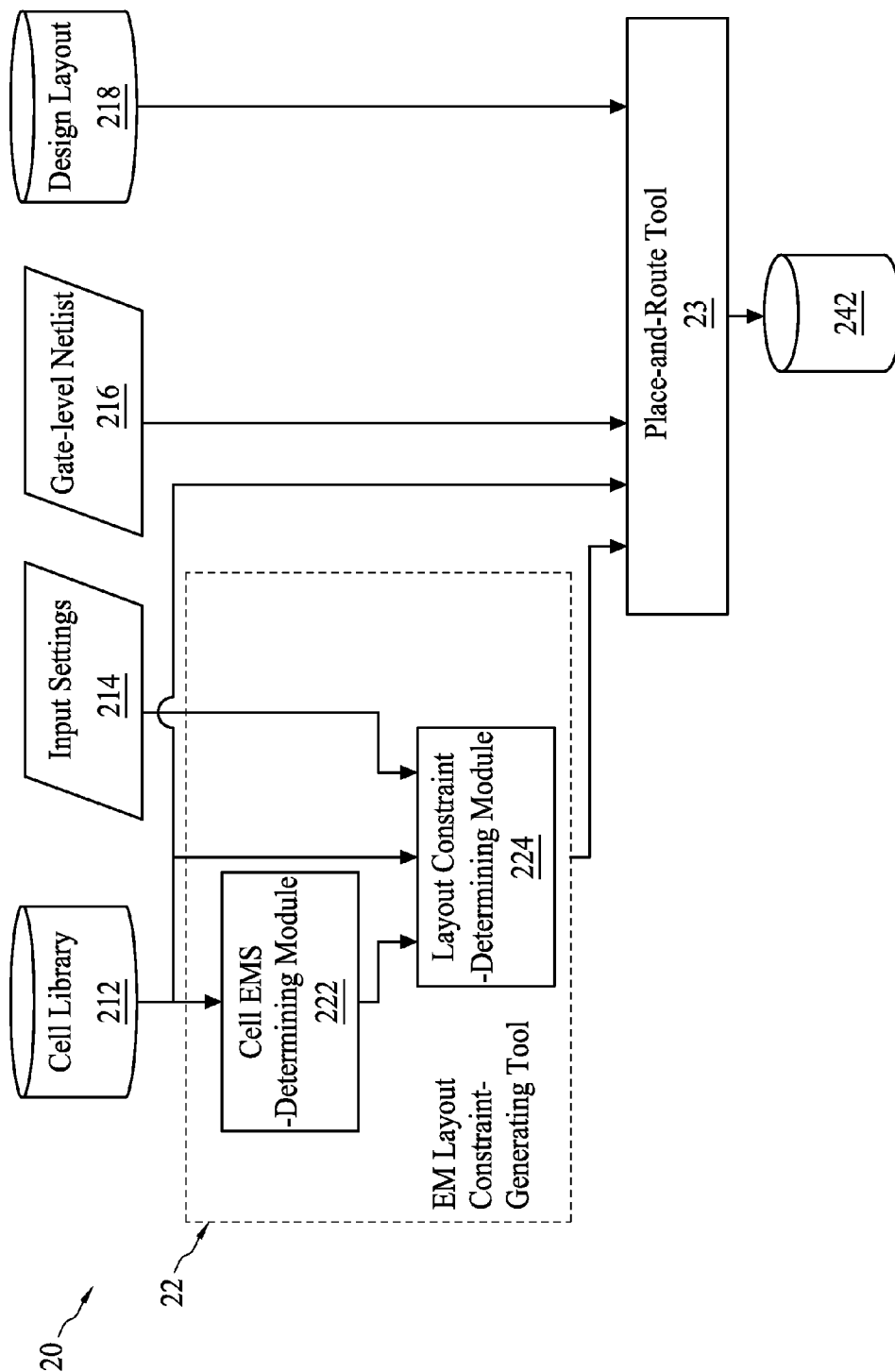


FIG. 2

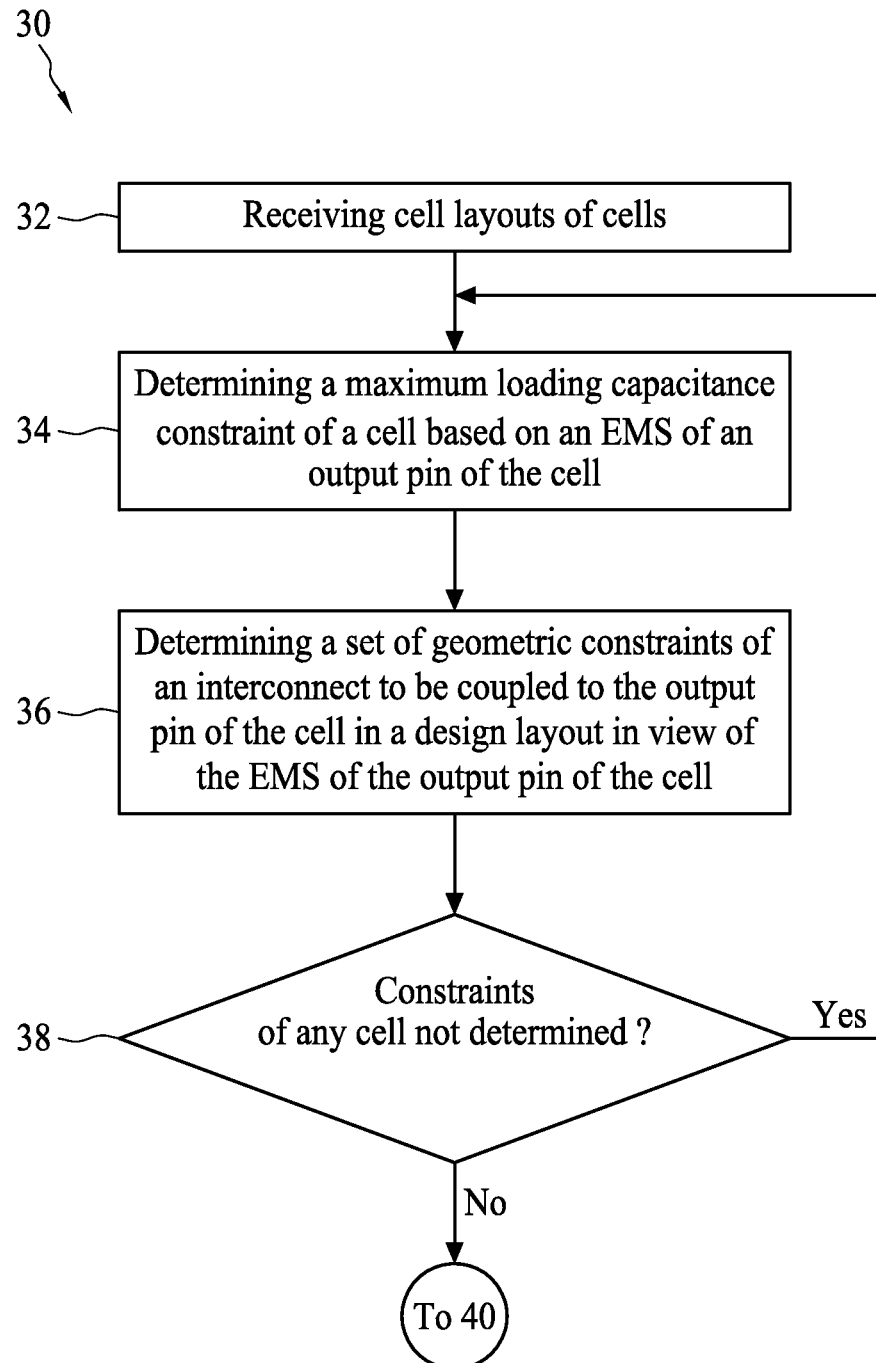


FIG. 3

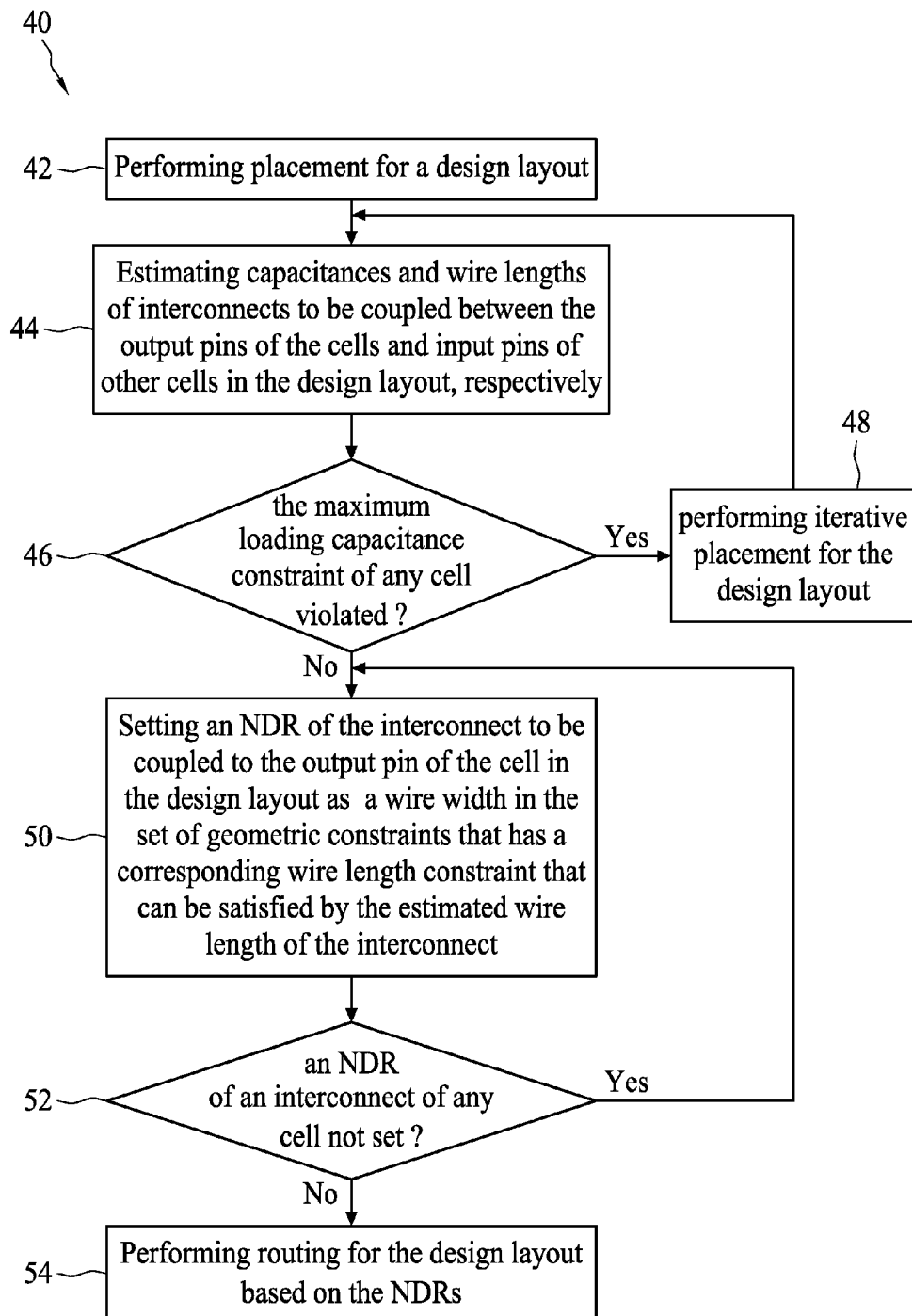


FIG. 4

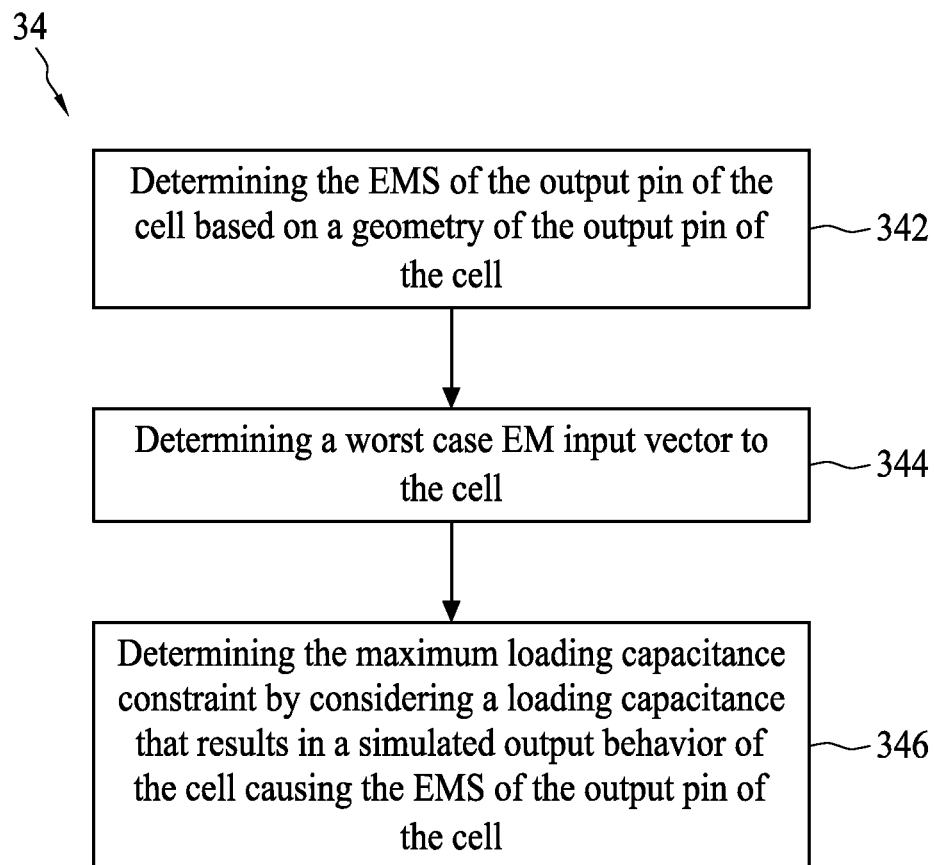


FIG. 5

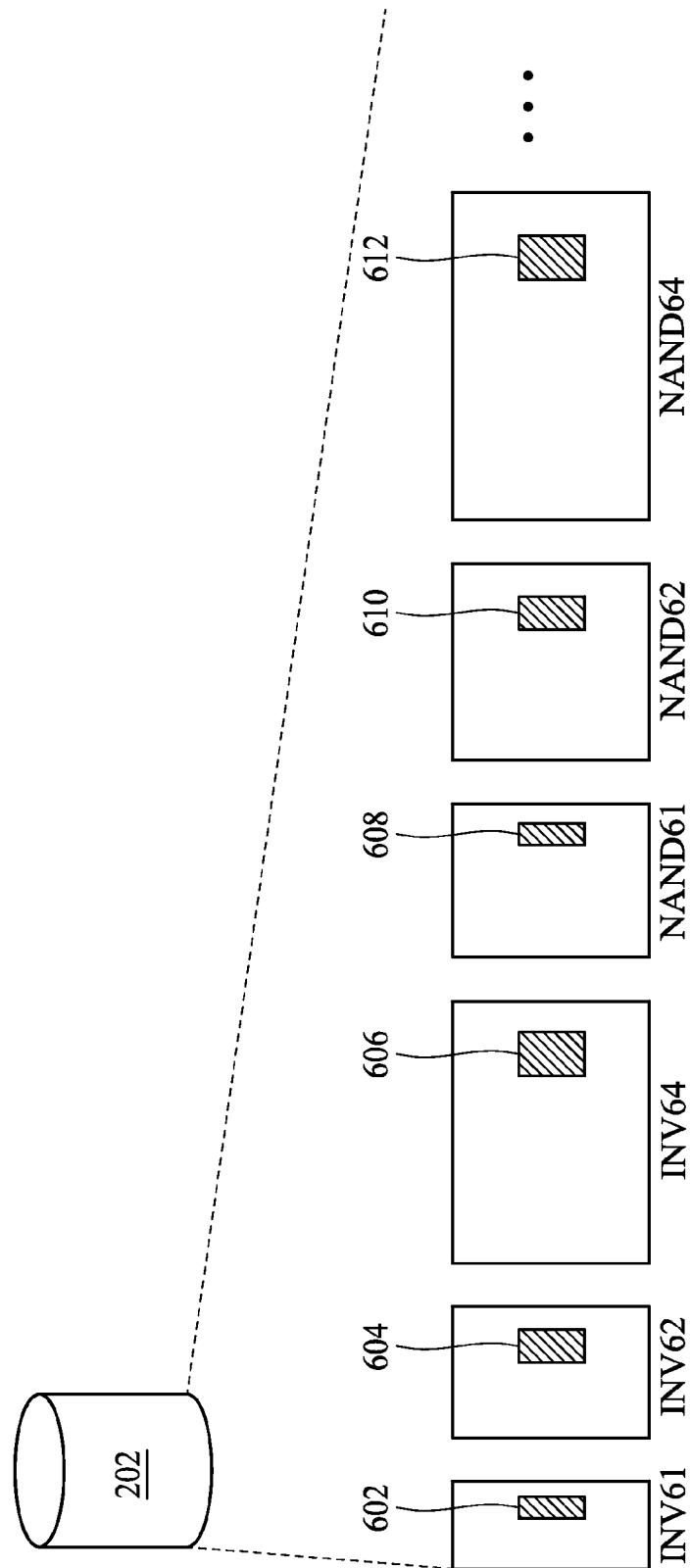


FIG. 6

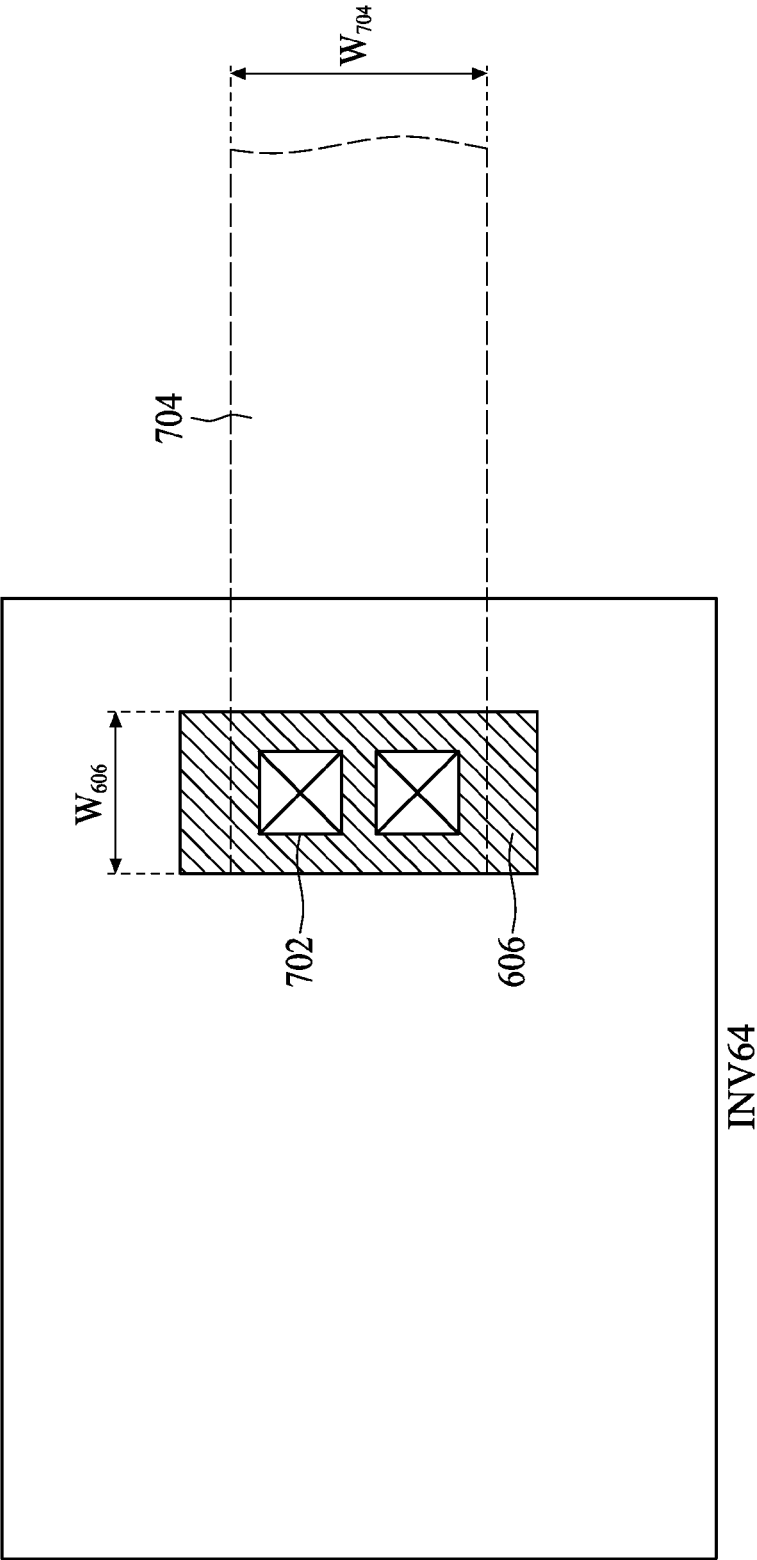


FIG. 7A

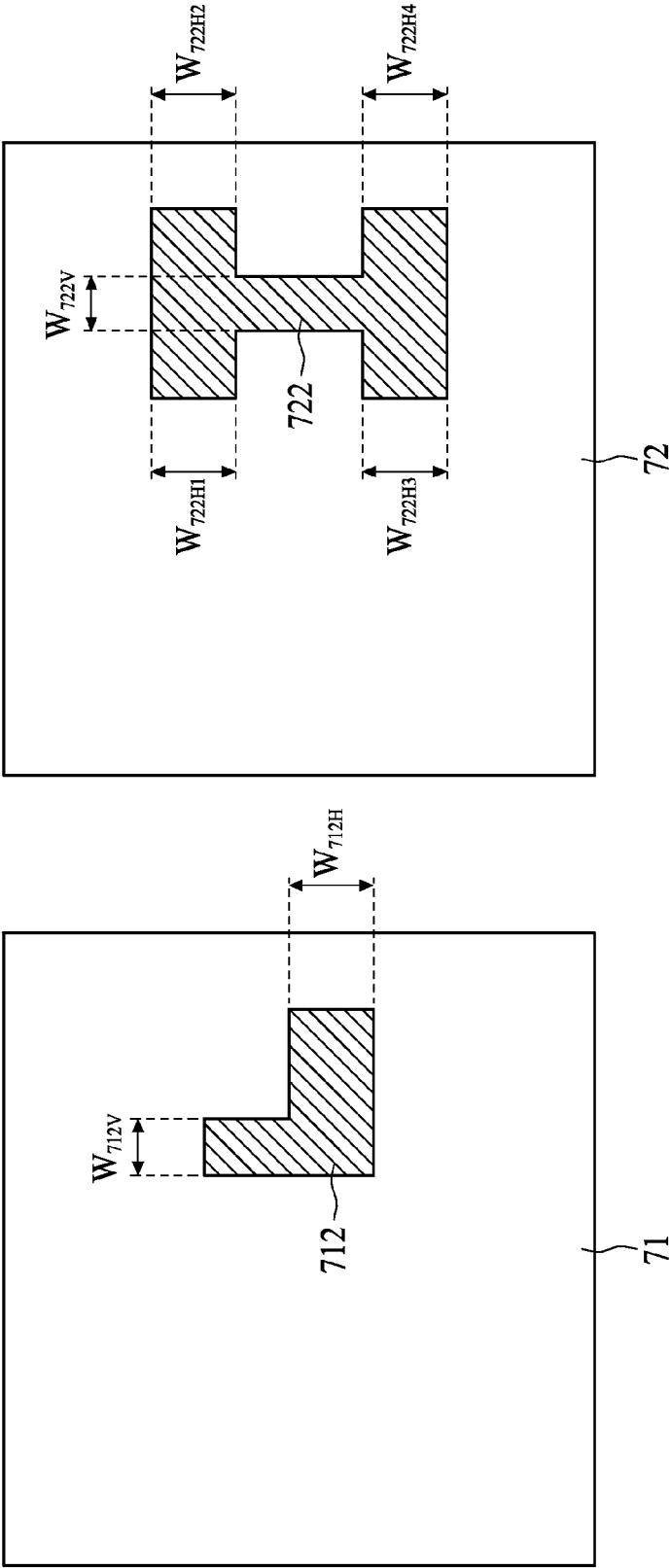


FIG. 7B

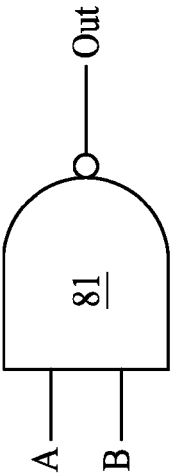


FIG. 8A

A	B	Out
0	0	1
0	1	1
1	0	1
1	1	0

FIG. 8B

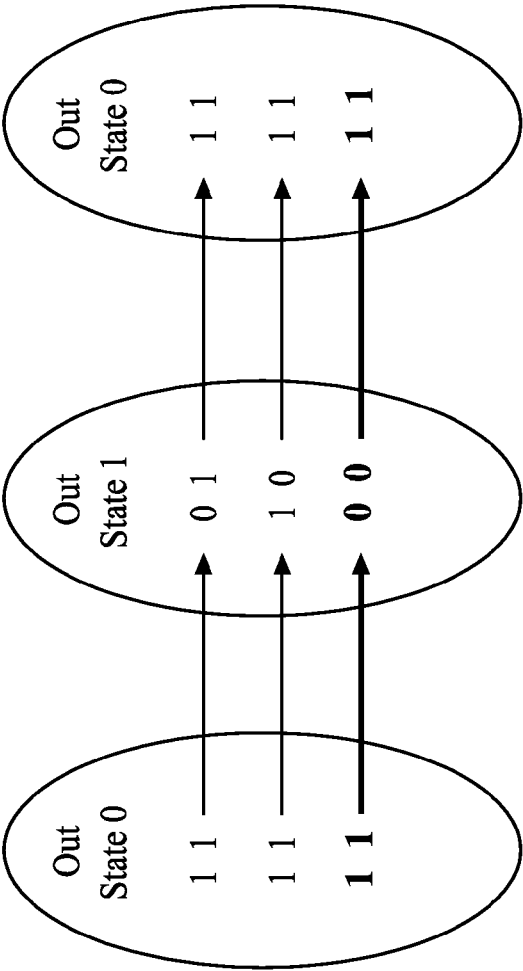


FIG. 8C

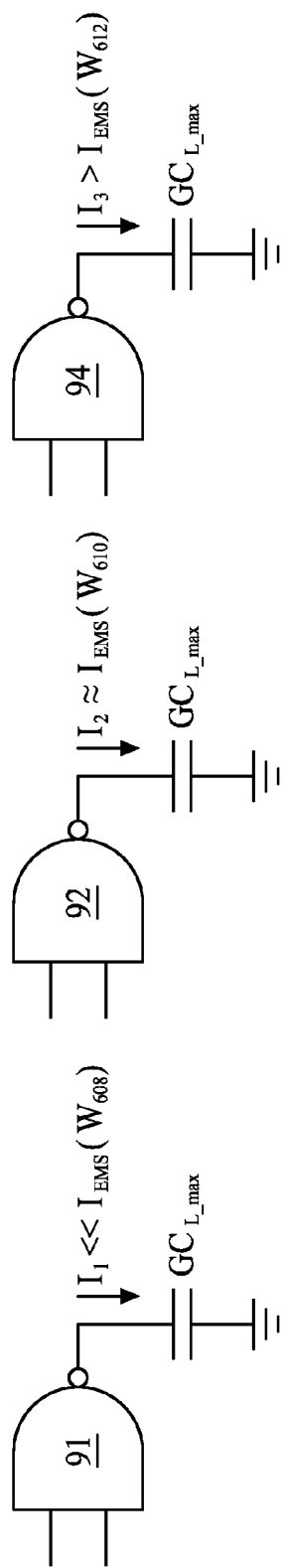


FIG. 9A

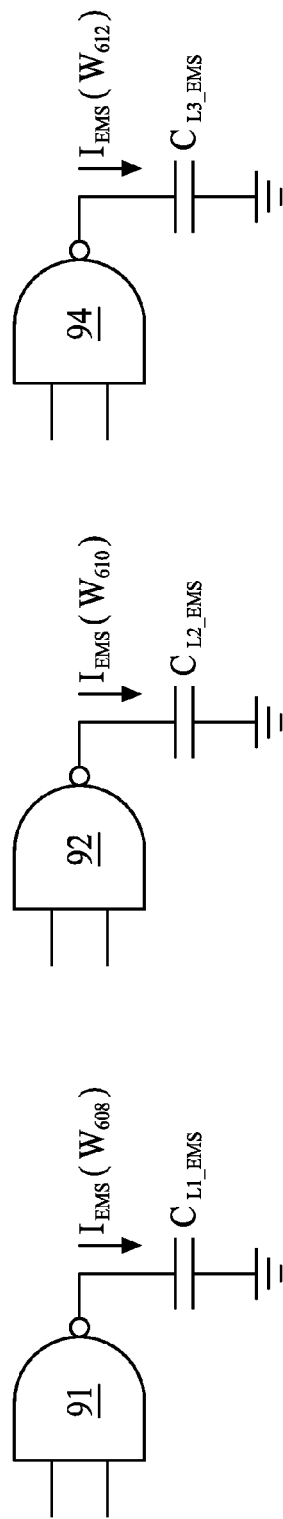


FIG. 9B

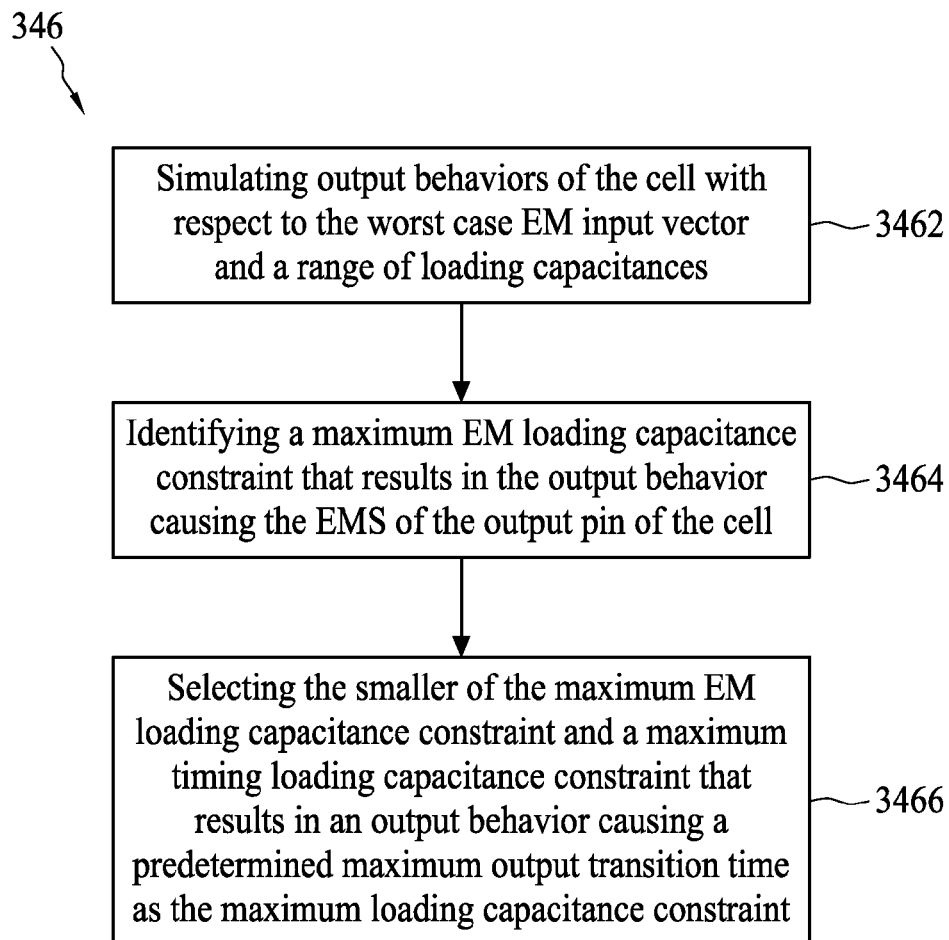


FIG. 10

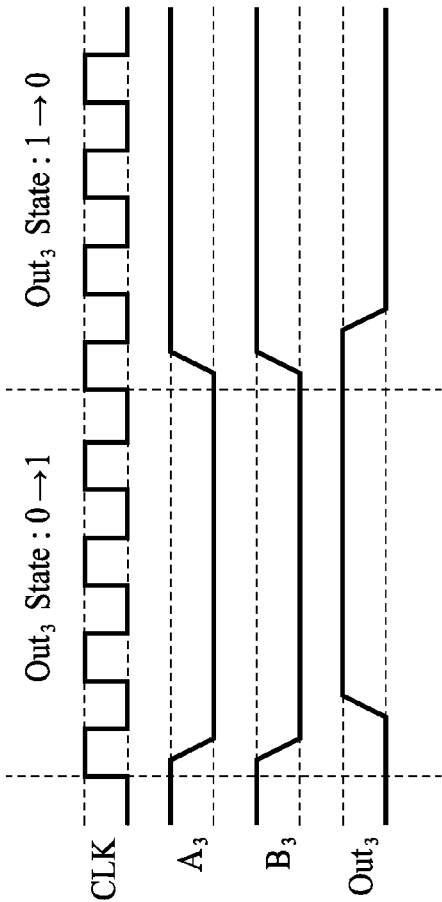


FIG. 12

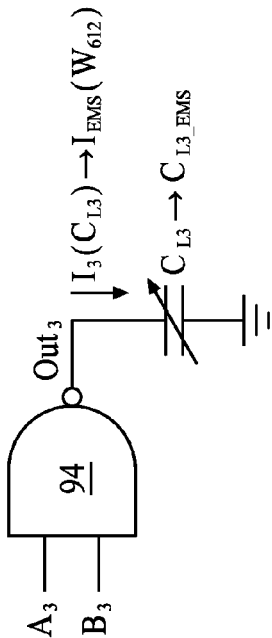


FIG. 11

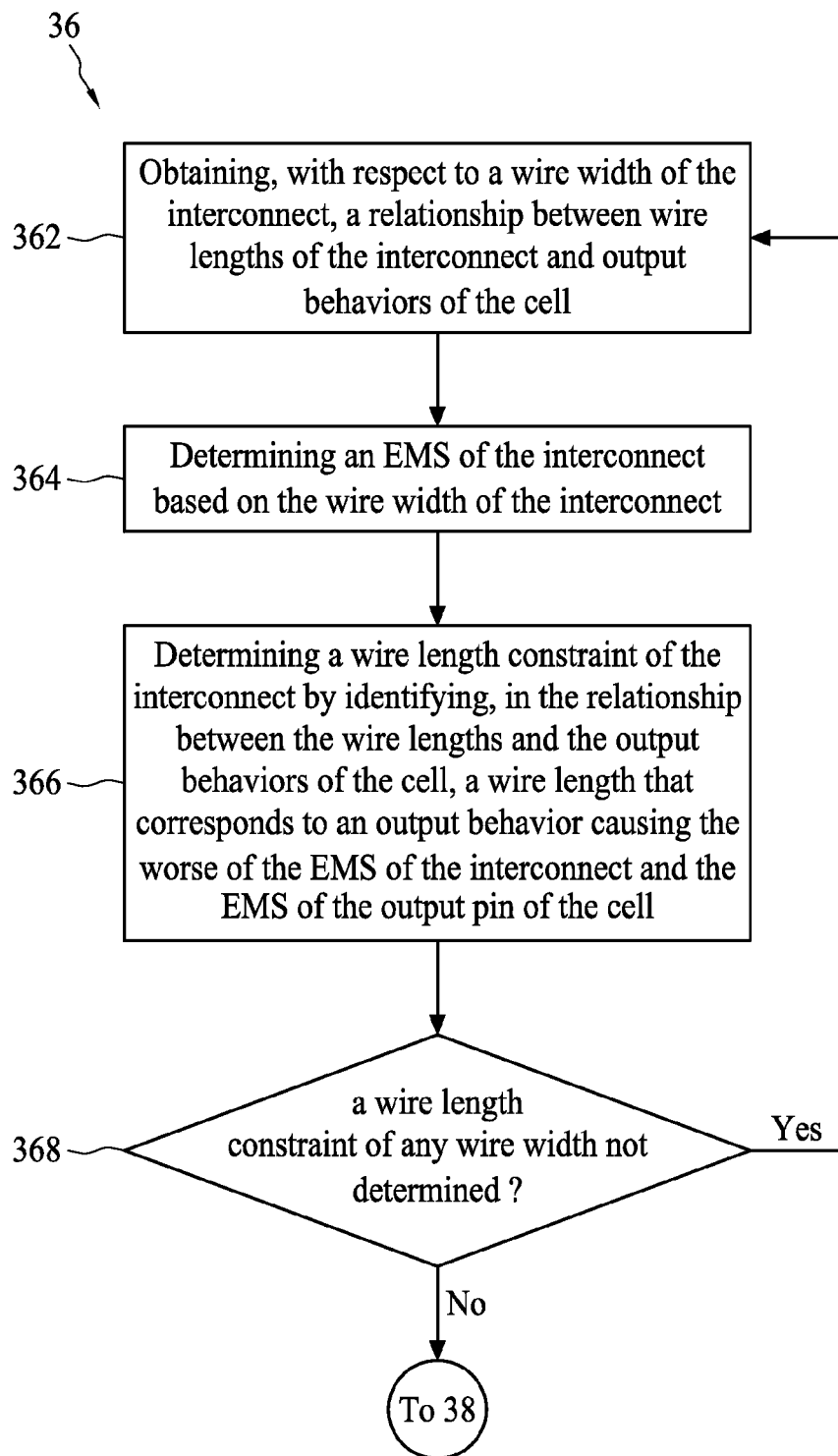


FIG. 13

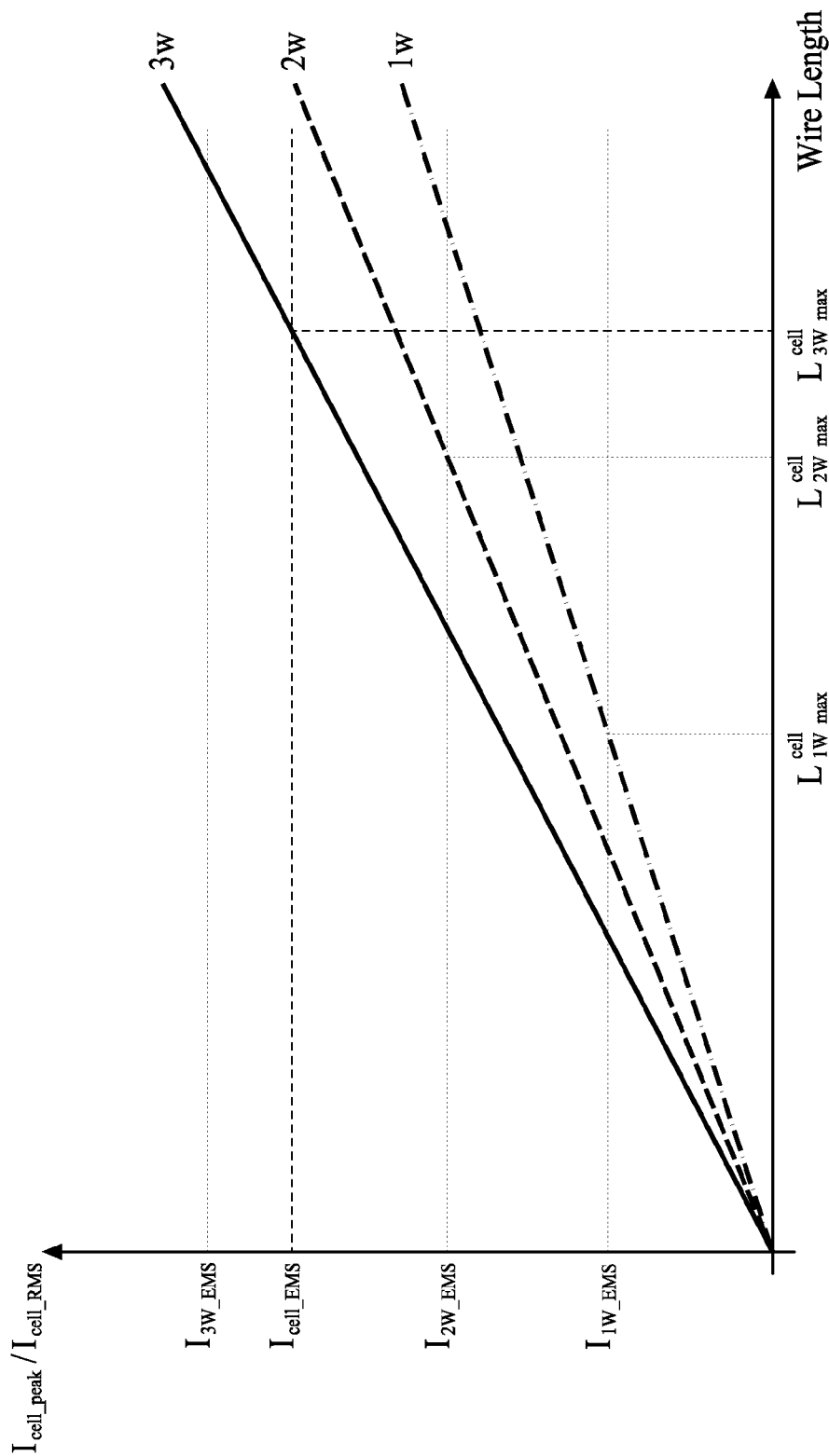


FIG. 14

1500

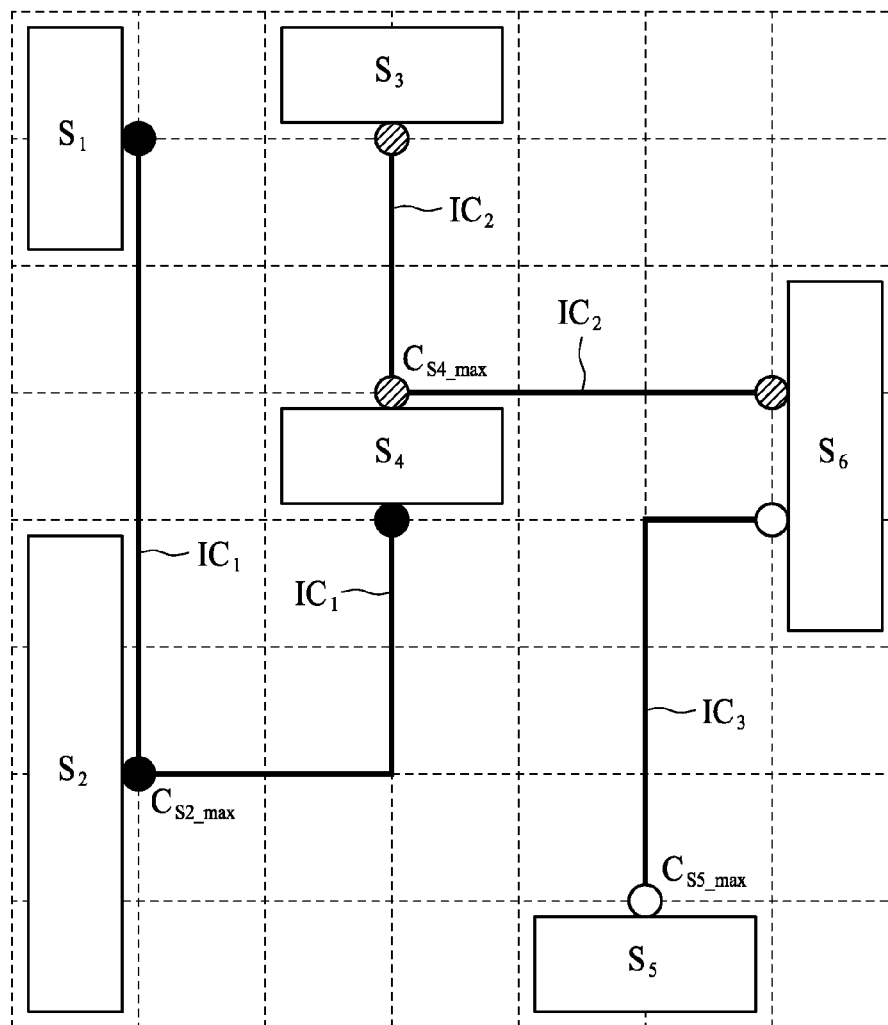


FIG. 15

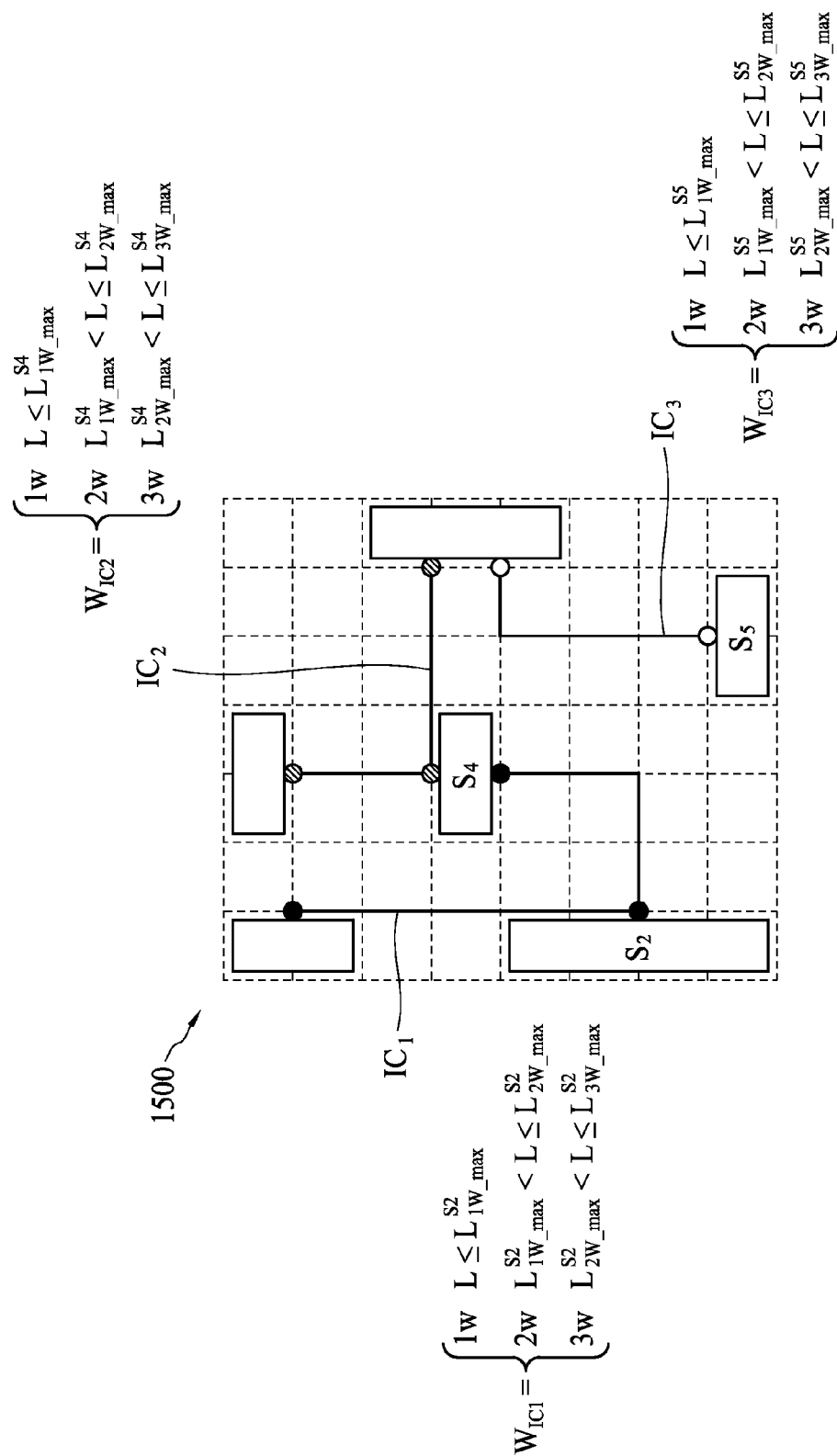


FIG. 16

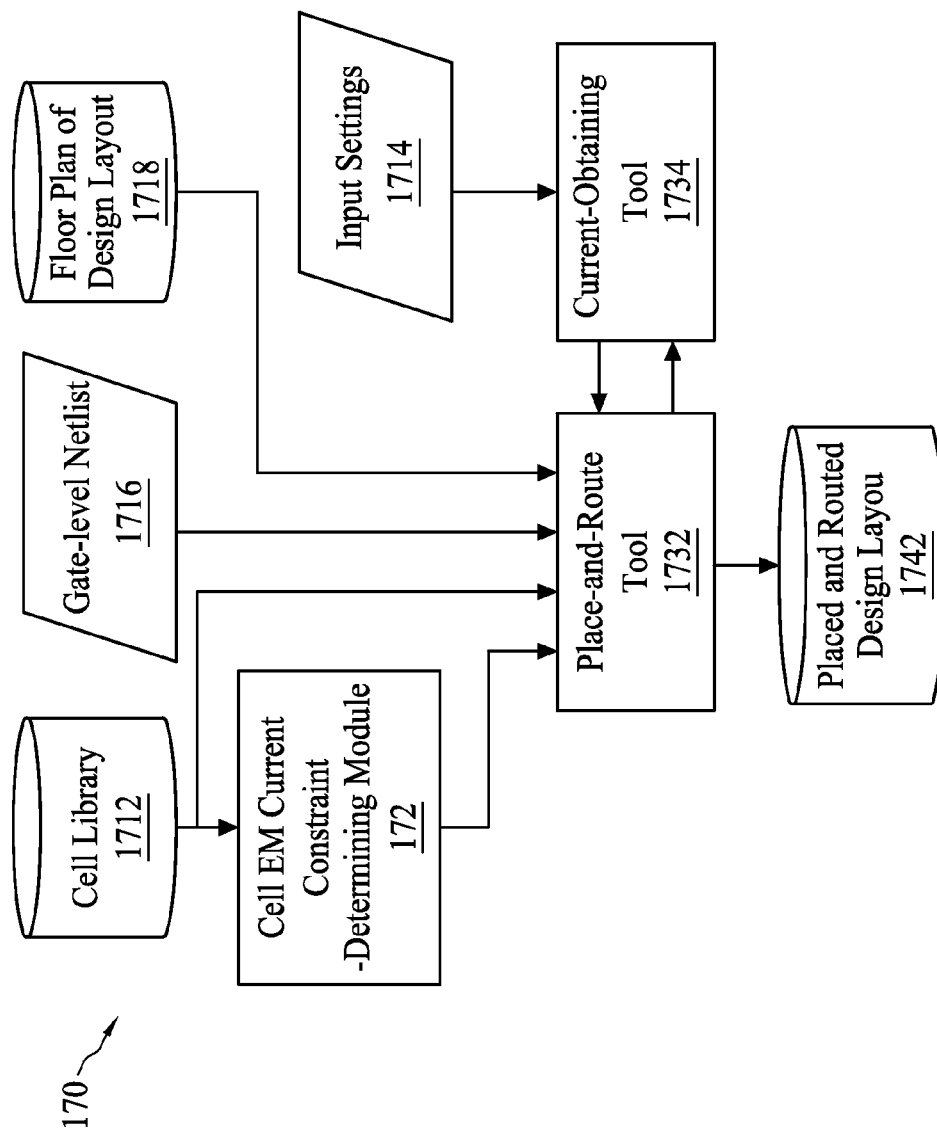


FIG. 17

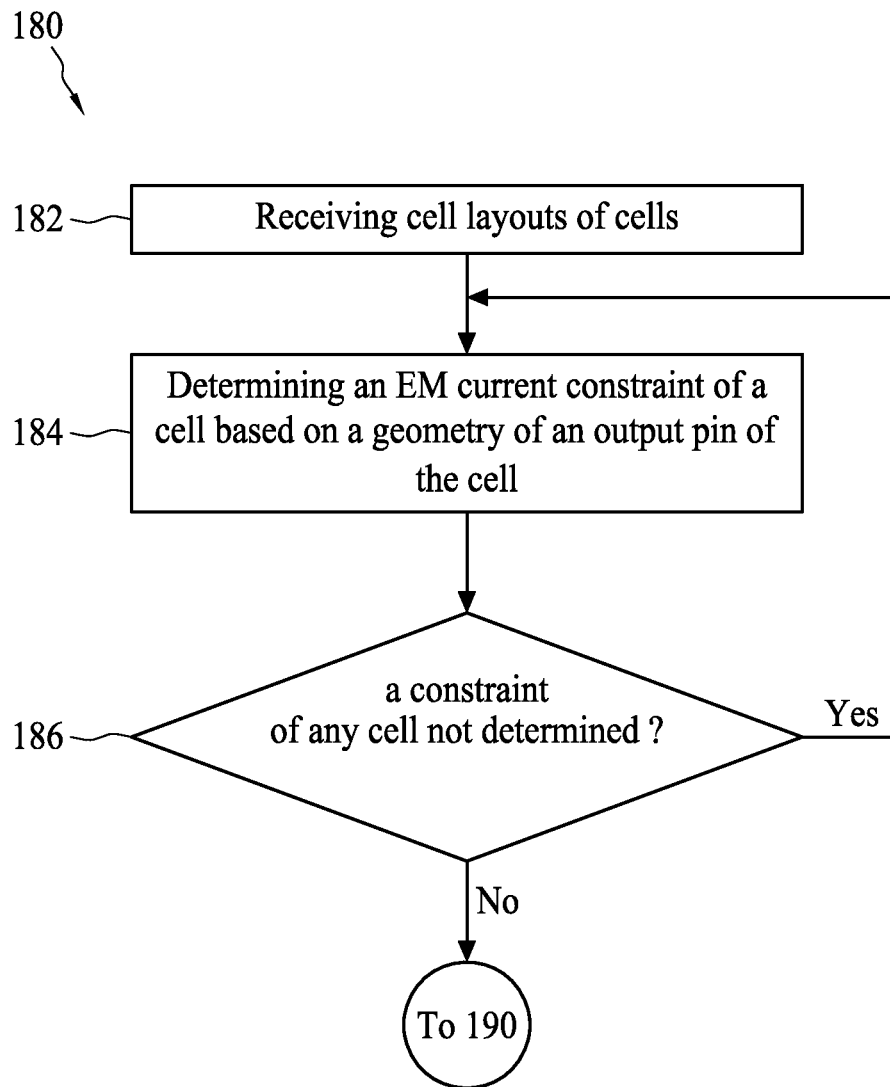


FIG. 18

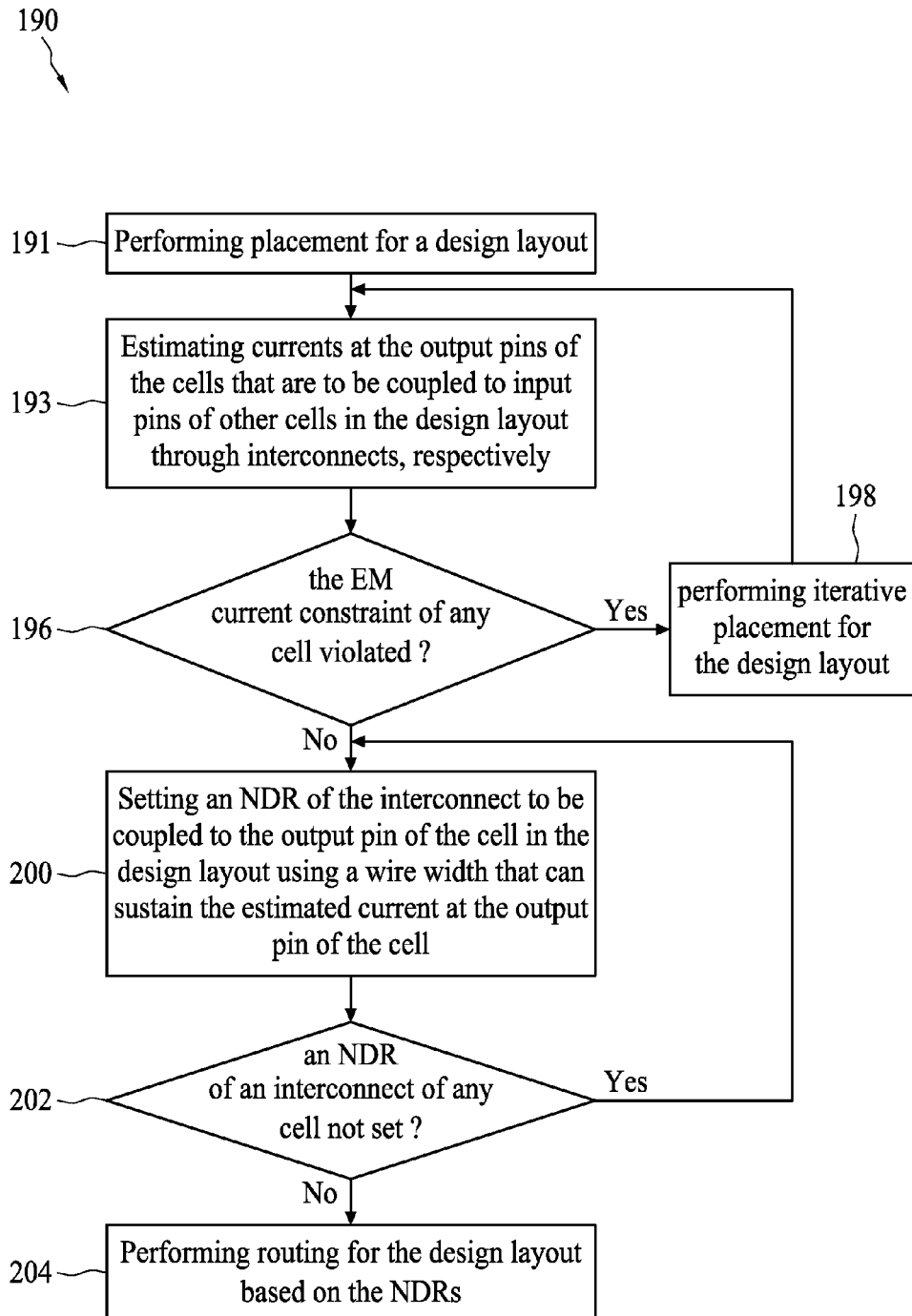


FIG. 19

2000

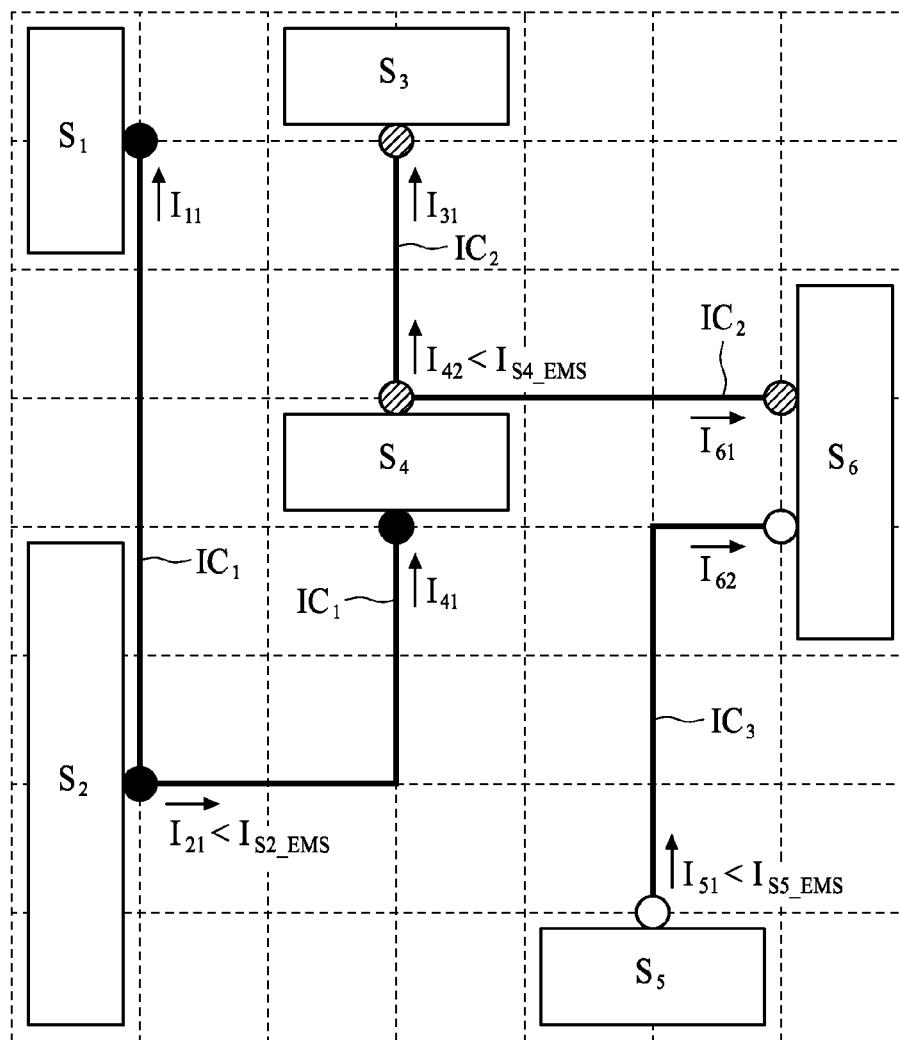


FIG. 20

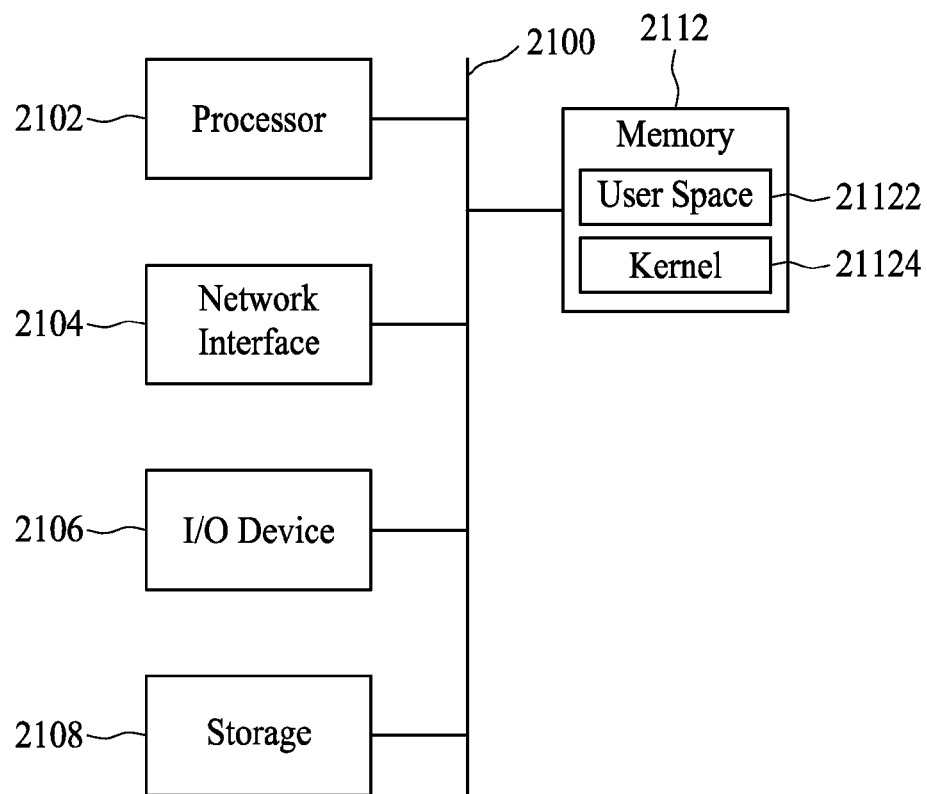
2100

FIG. 21

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ELECTROMIGRATION-AWARE LAYOUT GENERATION

BACKGROUND

With the continual scaling of feature size and the ever-expanding functionalities of chips, sizes of wires that connect components in a chip are also reduced, causing current densities through the wires to increase. A life span of a wire is subject to electromigration, which is a material transport caused by transfer of momentum between conducting electrons and metal ions. Electromigration can cause the formation of hillocks or voids in the wire, which can lead to short circuit or open circuit. A mean time to failure (MTTF) of the wire, when estimated taking electromigration into consideration, decreases with the increase of current density.

BRIEF DESCRIPTION OF THE DRAWINGS

Aspects of the present disclosure are best understood from the following detailed description when read with the accompanying figures. It is noted that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

FIG. 1 is a flow diagram of at least a portion of a cell design flow and a chip design flow of an integrated circuit chip in accordance with some embodiments.

FIG. 2 is a functional block diagram of an EM-aware layout generation system in accordance with some embodiments.

FIG. 3 is a flow diagram of an EM layout constraint-generating method in accordance with some embodiments.

FIG. 4 is a flow diagram of an EM-aware placement and routing method in accordance with some embodiments.

FIG. 5 is a flow diagram of a method performed in the operation 34 in FIG. 3 for determining a maximum loading capacitance constraint based on an EMS of an output pin of the cell in accordance with some embodiments.

FIG. 6 is a schematic diagram of a standard cell library in accordance with some embodiments.

FIG. 7A is a schematic diagram illustrating a situation in which an output behavior of an exemplary 4× inverter is limited by an EMS of the output pin in the cell layout of the 4× inverter, rather than by an EMS of an interconnect coupled to the output pin in accordance with some embodiments.

FIG. 7B is a schematic diagram illustrating a geometry of a multi-segment output pin in a cell layout used to determine the EMS of the cell with the cell layout in accordance with some embodiments.

FIGS. 8A to 8C illustrate a manner with which a worst case EM input vector of a NAND gate is determined in accordance with some embodiments.

FIG. 9A illustrates schematic circuit diagrams of a 1×NAND gate, a 2×NAND gate and a 4×NAND gate with a globally set maximum loading capacitance constraint.

FIG. 9B illustrates schematic circuit diagrams of a 1×NAND gate, a 2×NAND gate and a 4×NAND gate with respectively set maximum loading capacitance constraints in accordance with some embodiments.

FIG. 10 is a flow diagram of a method performed by the layout constraint-determining module in FIG. 2 or a method performed in the operation 346 in FIG. 5 for determining the maximum loading capacitance constraint in accordance with some embodiments.

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FIG. 11 is a schematic circuit diagram of a circuit for determining the maximum EM loading capacitance constraint of an exemplary 4×NAND gate in accordance with some embodiments.

FIG. 12 is a timing diagram that illustrates a frequency of operation and a toggle rate that affect the maximum EM loading capacitance constraint of the NAND gate in FIG. 11 in accordance with some embodiments.

FIG. 13 is a flow diagram of another method performed by the layout constraint-determining module in FIG. 2 or a method performed in the operation 36 in FIG. 3 for determining the set of geometric constraints of the interconnect in accordance with some embodiments.

FIG. 14 is a schematic diagram illustrating wire length constraints for interconnects of different wire widths under the EMS of the cell and the EMSes of the interconnects, respectively, in accordance to some embodiments.

FIG. 15 is a schematic diagram of a design layout in a process of placement in accordance with some embodiments.

FIG. 16 is a schematic diagram of a design layout in a process of assigning NDRs before routing in according with some embodiments.

FIG. 17 is a functional block diagram of an EM-aware layout generation system in accordance with other embodiments.

FIG. 18 is a flow diagram of an EM current constraint-generating method in accordance with some embodiments.

FIG. 19 is a flow diagram of an EM-aware placement and routing method in accordance with other embodiments.

FIG. 20 is a schematic diagram of the design layout in a process of placement in accordance with some embodiments.

FIG. 21 is a block diagram of a hardware system for implementing the software system embodiments described with references to FIG. 2 or 17, and the method embodiments described with reference to FIGS. 3 and 4, or FIGS. 18 and 19 in accordance with some embodiments.

DETAILED DESCRIPTION

The following disclosure provides many different embodiments, or examples, for implementing different features of the provided subject matter. Specific examples of elements and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. For example, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed between the first and second features, such that the first and second features may not be in direct contact. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed.

Further, spatially relative terms, such as “beneath,” “below,” “lower,” “above,” “upper,” “lower,” “left,” “right” and the like, may be used herein for ease of description to describe one element or feature’s relationship to another element(s) or feature(s) as illustrated in the figures. The spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. The apparatus may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein may likewise be interpreted accordingly. It will be understood that

when an element is referred to as being “connected to” or “coupled to” another element, it may be directly connected to or coupled to the other element, or intervening elements may be present.

FIG. 1 is a flow diagram of at least a portion of a cell design flow **100** and a chip design flow **150** of an integrated circuit (IC) chip in accordance with some embodiments. The cell design flow **100** provides physical designs of standard cells and characteristics of the cells for the cells to be employed as building blocks in the chip design flow **150**. The chip design flow **150** aims at implementing an IC chip design from a high-level specification to a physical layout which is verified for, for example, functionality, performance, and power. The flows **100** and **150** utilize one or more electronic design automation (EDA) tools to carry out one or more stages in the flows **100** and **150**.

In some embodiments, the cell design flow **100** includes a cell design stage **102** and a cell characterization stage **104**.

At the cell design stage **102**, cell design is performed at the transistor level and the circuits of the cells are physically laid out and verified according to specifications, technology-related information and design rules. Cell netlists and cell layouts are collected in a standard cell library. The term “netlist” used herein refers to both graphical-based representation such as a schematic and/or a text-based representation of a circuit.

At the cell characterization stage **104**, the physically implemented cells are characterized to facilitate the selection of the appropriate cells with respect to a design specification in the chip design flow **150**. For EM awareness in the chip design flow **150**, electromigration susceptibility (EMS) of the cells are characterized and collected in the standard cell library, as will be described in further detail with reference to FIG. 5.

In some embodiments, the chip design flow **150** includes an IC design stage **152**, a chip planning stage **154**, a placement stage **156**, a routing stage **158**, a parasitic extraction and analysis stage **160**, and a physical verification and signoff stage **162**. In the present disclosure, a digital design flow is used as an example. Other design flows, such as an analog standard cell design flow, are within the contemplated scope of the present disclosure.

At the IC design stage **152**, a design of the IC chip is provided by a circuit designer. For the digital design flow, a gate-level netlist is generated through logic synthesis based on the design by the circuit designer and the gates are mapped to the available cells in the standard cell library.

At the chip planning stage **154**, the gate-level netlist is partitioned into blocks and a floorplan for the blocks in a design layout of the IC chip is created.

At the placement stage **156**, the mapped cells of logic gates and registers in the blocks are placed at specific locations in the design layout. In some embodiments, constraints related to, for example, distances between the cells can be generated based on the characterized EMSes of the cells and applied when the placement are iteratively refined for a more EM-aware placement.

At the routing stage **158**, interconnects between the placed cells in the design layout are routed in accordance with routing constraints such as non-default routing (NDR) rules. The NDR relates to, for example, double or triple width wire, double or triple spacings between wires, a tapering rule, a number of via cuts, or other non-default via configurations. In some embodiments, NDRs for wire widths of the interconnects are generated based on the characterized EMSes of the cells and are applied during routing for the routing stage **158** to be more EM-aware.

At the parasitic extraction and analysis stage **160**, a physical netlist is extracted from the layout of the IC chip. The physical netlist includes parasitics such as parasitic resistors and capacitors introduced by the interconnects to the driver cells. Timing analysis can be performed on the physical netlist and post-route optimization can be performed on the design layout based on the analysis result to achieve timing closure of the chip design.

At the physical verification and signoff stage **162**, layout-versus-schematic (LVS) is performed on the physical netlist to ensure correspondence of the design layout to the gate-level netlist. Further, design rule check (DRC) is performed on the design layout to ensure the design clean of, for example, electrical issues, lithographic issues for manufacturing. Incremental fixing can be performed to achieve final signoff of the design before tape-out.

The cell design flow **100** and the chip design flow **150** in FIG. 1 are exemplary. Other sequence of the stages, partition of the stages, or additional stages before, between or after the stages shown are within the applicable scope of the present disclosure.

FIG. 2 is a functional block diagram of an EM-aware layout generation system **20** in accordance with some embodiments. The EM-aware layout generation system **20** includes an EM layout constraint-generating tool **22** and a place-and-route tool **23**. In some embodiments, the EM layout constraint-generating tool **22** is employed at the cell characterization stage **104** in the cell design flow **100** in FIG. 1 and the place-and-route tool **23** is used at the placement **156** and routing stage **158** in the chip design flow **150**. The EM layout constraint-generating tool **22** includes a cell EMS-determining module **222** and a layout constraint-determining module **224**. The cell EMS-determining module **222** is configured to receive cell layouts in a standard cell library **212**, and determine, for each cell, a respective EMS of an output pin of the cell. In some embodiments, the layout constraint-determining module **224** is configured to receive cell netlists in the standard cell library **212**, input settings **214** such as worst case EM input vectors for the cells, respectively, and the EMSes determined by the module **222** for the cells, respectively, and generate, for each cell, respective layout constraints that affect a geometry of an interconnect that will couple to the cell in a design layout. The place-and-route tool **23** is configured to receive a gate-level netlist **216** of a chip design, and a floorplan of a design layout **218** of the chip design, the cell layouts in the standard cell library **212**, and the layout constraints from the layout constraint-determining module **224**, and perform placement and routing in the design layout **218** in accordance with the layout constraints to generate a placed and routed design layout **242**.

FIG. 3 is a flow diagram of an EM layout constraint-generating method **30** in accordance with some embodiments. In some embodiments, the method **30** is performed during the cell characterization stage **104** in FIG. 1. In operation **32**, cell layouts of several cells such as standard cells in a standard cell library are received. In operation **34**, for a cell, a maximum loading capacitance constraint is determined based on an EMS of an output pin of the cell. In operation **36**, a set of geometric constraints of an interconnect that will be coupled to the output pin of the cell in a design layout is determined in view of the EMS of the output pin of the cell. In operation **38**, if layout constraints for any cell in the standard cell library are not determined, the method **30** loops back to the operation **34** to determine the layout constraints for another cell; otherwise, the layout constraints for the cells are generated and available for use in an EM-aware placement and routing method **40** in FIG. 4.

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FIG. 4 is a flow diagram of the EM-aware placement and routing method 40 in accordance with some embodiments. In some embodiments, the method 40 is performed in the placement stage 156 and routing stage 158 in FIG. 1. In operation 42, placement for a design layout that includes the cells is performed. In operation 44, capacitances and wire lengths of interconnects to be coupled between the output pins of the cells and input pins of other cells in the design layout are estimated, respectively. In operation 46, if the maximum loading capacitance constraint of any cell in the design layout is violated, then the method 40 performs iterative placement for the design layout in operation 48 and loops back to the operation 44. If the maximum loading capacitance constraints of all the cells in the design layout are satisfied, then the method 40 proceeds to operation 50. In operation 50, for a cell in the design layout, an NDR of the interconnect to be coupled to the output pin of the cell is set according to a wire width in the set of geometric constraints that has a corresponding wire length constraint that can be satisfied by the estimated wire length of the interconnect. In operation 52, if an NDR of an interconnect of any cell in the design layout is not set, the method 40 loops back to the operation 50 to set the NDR for another cell; otherwise, routing for the design layout is performed based on the NDRs in operation 54.

FIG. 5 is a flow diagram of a method performed in the operation 34 in FIG. 3 for determining a maximum loading capacitance constraint based on an EMS of an output pin of the cell in accordance with some embodiments. In operation 342, the EMS of the output pin of the cell is determined based on the geometry of the output pin of the cell. In operation 344, a worst case EM input vector to the cell is determined. In operation 346, the maximum loading capacitance constraint is determined by considering a loading capacitance that results in a simulated output behavior of the cell causing the EMS of the output pin of the cell.

FIG. 6 is a schematic diagram of a standard cell library 212 in accordance with some embodiments. In the embodiments described with reference to FIG. 2, the standard cell library 212 is received by the cell EMS-determining module 222. In the embodiments described with reference to FIG. 3, in operation 32, the cell layouts INV61, INV62, INV64, NAND61, NAND62, NAND64, . . . of a minimum-sized (1×) inverter, a double-sized (2×) inverter, a quadruple-sized (4×) inverter, a 1×NAND gate, a 2×NAND gate, a 4×NAND gate, . . . are received. As illustrated in FIG. 6, the standard cell library 212 includes cell layouts of standard cells such as the cell layout INV61 of the 1× inverter, the cell layout INV62 of the 2× inverter, the cell layout INV64 of the 4× inverter, the cell layout NAND61 of the 1×NAND gate, the cell layout NAND62 of the 2×NAND gate, the cell layout NAND 64 of the 4×NAND gate and so forth. Each cell layout INV61, INV62, INV64, NAND 61, NAND62 or NAND 64 has a respective output pin 602, 604, 606, 608, 610 or 612. In some embodiments, the widths of the output pins 602, 604 and 606, or 608, 610 and 612 increase with as the sizes of the gates increase from 1× to 4×. Other sizing arrangements of the output pins are within the contemplated scope of the present disclosure.

FIG. 7A is a schematic diagram illustrating a situation in which an output behavior of an exemplary 4× inverter is limited by an EMS of the output pin 606 in the cell layout INV64 of the 4× inverter, rather than by an EMS of an interconnect 704 coupled to the output pin 606 in accordance with some embodiments. In the embodiments described with reference to FIG. 2, the EM layout constraint-generating tool 22 employs the cell EMS-determining module 222 to determine the EMS of the output pin 606 of the 4× inverter, and the

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layout constraint-determining module 224 to determine the layout constraint that affects the geometry of the interconnect to be coupled to the 4× inverter according to the EMS of the output pin 606 of the 4× inverter. In the embodiments described with reference to FIG. 3, in operations 34 and 36, the maximum loading capacitance constraint of the 4× inverter and the set of geometric constraints of the interconnect to be coupled to the output pin 606 of the 4× inverter in the design layout are determined based on the EMS of the output pin 606 of the cell. In some embodiments, an EMS of a wire is a current limit of the wire to ensure a certain EM reliability of the wire. In some embodiments, failure due to EM of a wire is expressed by Black's equation:

$$MTTF = \frac{A}{J^2} \cdot \exp\left(\frac{E_a}{k \cdot T}\right) \quad (1)$$

where A is a material constant, J is a current density, E_a is an activation energy, k is the Boltzmann constant, and T is a temperature. To ensure a certain EM reliability of the wire, a current density J of the wire at a corresponding temperature T is limited to achieve a target MTTF. The current density limit can be a peak current density limit, an average current density limit, a DC current density limit, or a root mean square (RMS) current density limit. Current density limits at corresponding temperatures are usually defined as EM design rules in a design rule manual. Based the corresponding EM design rule, a width and a predetermined thickness of the wire, a current limit such as a peak current limit, an average current limit, a DC current limit, or an RMS current limit of the wire is calculated. In some embodiments, the EMS of the wire is reflected by the current limit of the wire. In other words, the smaller the current limit of the wire is, the greater the EMS of the wire is. As shown in FIG. 7A, a width W_{606} of the output pin 606 is smaller than a width W_{704} of the interconnect 704 coupled to the output pin 606 through vias 702. By applying the width W_{606} and the width W_{704} to the same EM design rule, respectively, the obtained current limit of the output pin 606 is smaller than that of the interconnect 704. Therefore, the output behavior such as the output current of the 4× inverter is limited by the EMS such as the current limit of the output pin 606, rather than by the EMS such as the current limit of the interconnect 704.

Referring to FIG. 7A, in the embodiments described with reference to FIG. 2, the cell EMS-determining module 222 determines the respective EMS for each cell such as the 4× inverter in the standard cell library 212 based on the width W_{606} of the output pin 606 of the 4× inverter. In the embodiments described with reference to FIG. 5, in operation 342, the EMS of the output pin 606 of the 4× inverter is determined based on the width W_{606} of the output pin 606 of the 4× inverter. In FIG. 7A, the output pin 606 of the 4× inverter is exemplarily shown as a single line segment. Therefore, the width W_{606} of the output pin 606 for determining the EMS of the output pin 606 is the width of the line segment. In other embodiments described in the following, the output pin has multiple line segments.

FIG. 7B is a schematic diagram illustrating a geometry of a multi-segment output pin 712 or 722 in a cell layout 71 or 72 used to determine the EMS of the cell in accordance with some embodiments. A width of the output pin 712 or 722 for determining an EMS of the output pin 712 or 722 is a width of the thinnest segment of the output pin 712 or 722. For example, the output pin 712 has an L shape and is formed by a vertical segment with a width W_{712V} and a horizontal seg-

ment with a width W_{712H} . The width W_{712V} is thinner than the width W_{712H} and is selected as the geometry of the output pin 712 for calculating the EMS of the cell with the cell layout 71. For another example, the output pin 722 has an I shape, and is formed by a vertical segment with a width W_{722V} , two horizontal segments with widths W_{722H1} and W_{722H3} , respectively, on one side of the vertical segment, and two horizontal segments with widths W_{722H2} and W_{722H4} , respectively, on the other side of the vertical segment. The width W_{722V} is the thinnest among the widths W_{722V} , W_{722H1} , W_{722H2} , W_{722H3} and W_{722H4} and is selected as the geometry of the output pin 722 for calculating the EMS of the cell with the cell layout 72. Further, in some embodiments, if a predefined region in an output pin where vias for coupling the output pin to an interconnect will be formed is known at the cell characterization stage 104 in FIG. 1, a width of the thinnest segment of the predefined region is used to calculate the EMS of the cell. In addition, in some embodiments, if a predefined region in an output pin where via formation is forbidden is known at the cell characterization stage 104 in FIG. 1, the predefined region is avoided when identifying the width for calculating the EMS of the output pin of the cell.

FIGS. 8A to 8C illustrate a manner with which a worst case EM input vector of a NAND gate 81 is determined in accordance with some embodiments. FIG. 8A is a schematic circuit diagram of a NAND gate 81. FIG. 8B is a truth table of the NAND gate 81. FIG. 8C illustrate the possible input vectors causing the 0→1 transition and 1→0 transition in the output Out of the NAND gate 81. In the embodiments described with reference to FIG. 2, for generating the layout constraint that affects the geometry of the interconnect coupled to the output pin of the cell such as the NAND gate 81, the layout constraint-determining module 224 receives the input settings 214 that contain the worst case EM input vector (1,1)→(0,0)→(1,1). In the embodiments described with reference to FIG. 5, in operation 344, the worst case EM input vector (1,1)→(0,0)→(1,1) to the NAND gate 81 is determined. In FIG. 8A, the NAND gate 81 has two inputs A and B, and an output Out. In FIG. 8B, for generating the worst case EM input vector, the truth table of the NAND gate 81 is generated. In the truth table, outcome states of the output Out with respect to enumerated states of received inputs are generated. According to the truth table in FIG. 8B, when the inputs A and B are both “1”, the state of the output Out is “0”, and when either or both the inputs A and B are “0”, the state of the output Out is “1”. Then, as shown in FIG. 8C, based on the truth table in FIG. 8B, possible input vectors that cause the output Out to toggle from a first state to a second state such as 0→1 or 1→0, and then toggling from the second state to the first state such as 1→0 or 0→1 are obtained. An input vector is a sequence of inputs that cause the output transitions 0→1 and 1→0. In FIG. 8C, there are three possible input vectors that will cause the output Out to transition from “0” to “1” and then “1” to “0”. The first input vector of the inputs A and B is (1,1)→(0,1)→(1,1). In other words, the input A transitions from “1” to “0” and then from “0” to “1” while the input B stays at “1”. The second input vector of the inputs A and B is (1,1)→(1,0)→(1,1). In other words, the input B transitions from “1” to “0” and then from “0” to “1” while the input A stays at “1”. The third input vector of the inputs A and B is (1,1)→(0,0)→(1,1). In this case, both the inputs A and B transition from “1” to “0” and then from “0” to “1”. After the possible input vectors are generated, an output current such as a peak output current or an RMS output current in response to each input vector is determined by, for example, simulations. The input vector with the largest output current is the worst case EM input

vector. For the NAND gate 81, the worst case EM input vector is the one with both the inputs A and B transition from “1” to “0” and then from “0” to “1”.

FIG. 9A illustrates schematic circuit diagrams of a 1×NAND gate 91, a 2×NAND gate 92 and a 4×NAND gate 94 with a globally set maximum loading capacitance constraint. In comparison to FIG. 9A, FIG. 9B illustrates schematic circuit diagrams of a 1×NAND gate 91, a 2×NAND gate 92 and a 4×NAND gate 94 with respectively set maximum loading capacitance constraints in accordance with some embodiments. Referring to FIG. 9B, in the embodiments described with reference to FIG. 2, the layout constraint-determining module 224 generates the layout constraint C_{L1_EMS} , C_{L2_EMS} or C_{L3_EMS} of the interconnect to be coupled to the output pin 608, 610 or 612 shown in FIG. 6 of the cell 91, 92 or 94 based on the cell netlist in the standard cell library 212, the cell EM current limit $I_{EMS}(W_{608})$, $I_{EMS}(W_{610})$ or $I_{EMS}(W_{612})$ determined by the cell EMS-determining module 222 and the input settings 214 containing the worst case EM input vector. In the embodiments described with reference to FIG. 5, in operation 346, the maximum loading capacitance constraint C_{L1_EMS} , C_{L2_EMS} or C_{L3_EMS} is determined by considering a loading capacitance that results in a simulated output behavior of the cell 91, 92 or 94 causing the EM current limit $I_{EMS}(W_{608})$, $I_{EMS}(W_{610})$ or $I_{EMS}(W_{612})$ of the output pin 608, 610 or 612 of the cell 91, 92 or 94. For comparison purpose, in FIG. 9A, the global maximum loading capacitance constraint GC_{L_max} is applied to each of the 1×NAND gate 91, 2×NAND gate 92 and 4×NAND gate 94. Suppose under the global maximum loading capacitance constraint GC_{L_max} , the 2×NAND gate 92 has an output current I_2 such as a peak current closer to causing the EM current limit $I_{EMS}(W_{610})$ of the output pin 610 of the 2×NAND gate 92. Under the same maximum loading capacitance constraint GC_{L_max} , the 4×NAND gate 94 has an output current I_3 that is larger than the output current I_2 of the 2×NAND gate 92 due to a higher driving strength. The output current I_3 may be even larger than the EM current limit $I_{EMS}(W_{612})$ of the output pin 612 of the 4×NAND gate 92, thereby resulting in an EM violation. On the other hand, under the same maximum loading capacitance constraint GC_{L_max} , the 1×NAND gate 91 has an output current I_1 that is smaller than the output current I_2 due to a lower driving strength. Although the output current I_1 is smaller than the EM current limit $I_{EMS}(W_{608})$ of the output pin 608 of the 1×NAND gate 91, the output current I_1 may be so small that causes a timing violation. Therefore, in the embodiments in FIG. 9B, each of the 1×NAND gate 91, 2×NAND gate 92 and 4×NAND gate 94 has a respective maximum EM loading capacitance constraint C_{L1_EMS} , C_{L2_EMS} or C_{L3_EMS} in accordance with the respective EMS $I_{EMS}(W_{608})$, $I_{EMS}(W_{610})$ or $I_{EMS}(W_{612})$ of the output pin 608, 610 or 612.

FIG. 10 is a flow diagram of a method performed by the layout constraint-determining module 224 in FIG. 2 or a method performed in the operation 346 in FIG. 5 for determining the maximum loading capacitance constraint in accordance with some embodiments. In operation 3462, with respect to the worst case EM input vector and a range of loading capacitances, output behaviors of the cell are simulated. In the operation 3462, instead of performing simulations for each possible input vectors, a simulation is performed using the worst case EM input vector for each value of loading capacitance. In operation 3464, a maximum EM loading capacitance constraint that results in the output behavior causing the EMS of the output pin of the cell is identified. In operation 3466, the smaller of the maximum EM loading capacitance constraint and a maximum timing

loading capacitance constraint that results in an output behavior causing a predetermined maximum output transition time is selected as the maximum loading capacitance constraint.

FIG. 11 is a schematic circuit diagram of a circuit for determining the maximum EM loading capacitance constraint of the exemplary 4xNAND gate 94 in accordance with some embodiments. In operation 3462 in FIG. 10, the output currents $I_3(C_{L3})$ of the cell are simulated with respect to the worst case EM input vector and the range of loading capacitances C_{L3} . In operation 3464, the maximum EM loading capacitance constraint C_{L3_EMS} that results in the output current $I_3(C_{L3})$ causing the EM current limit $I_{EMS}(W_{612})$ of the output pin 612 of the cell 94 is identified. In FIG. 11, the output currents $I_3(C_{L3})$ of the NAND gate 94 are simulated with respect to the worst case EM input vector for the inputs A_3 and B_3 described with reference to 8C while sweeping the loading capacitance C_{L3} of the NAND gate 94. The output current $I_3(C_{L3})$ that matches the EMS $I_{EMS}(W_{612})$ of the output pin 612 of the NAND gate 94 is determined to be the maximum EM loading capacitance constraint C_{L3_EMS} of the NAND gate 94. In some embodiments, the simulations are performed using a SPICE circuit simulator.

In operation 3466 in FIG. 10, the smaller of the maximum EM loading capacitance constraint C_{L3_EMS} and the maximum timing loading capacitance constraint that results in the output behavior causing the predetermined maximum output transition time is selected as the maximum loading capacitance constraint. Referring to FIG. 11, in some embodiments, the maximum timing loading capacitance constraint is determined by sweeping the loading capacitance C_{L3} while simulating an output voltage Out_3 with respect to a worst case input vector, and identifying a loading capacitance that results in the output voltage Out_3 that has the same output transition time as the predetermined maximum output transition time.

Furthermore, other input settings such as a frequency of operation of the chip design and a toggle rate of the cell in the chip design can affect the maximum EM loading capacitance constraint C_{L3_EMS} of the cell 94. FIG. 12 is a timing diagram that illustrates the frequency of operation and the toggle rate that affect the maximum EM loading capacitance constraint C_{L3_EMS} of the NAND gate 94 in FIG. 11 in accordance with some embodiments. After the IC design stage 152 in FIG. 1, a pre-layout simulation of the design layout is performed. A timing diagram such as the timing diagram in FIG. 12 can be generated by the pre-layout simulation. The frequency of operation of the chip design is a frequency of a clock signal CLK generated by a clock circuit of the design layout. The higher the frequency of operation is, the more frequent the output Out_3 of the NAND gate 94 transitions and therefore the higher the RMS current $I_3(C_{L3})$ in FIG. 11 is. Correspondingly, the maximum EM loading capacitance constraint is changed so that the RMS current $I_3(C_{L3})$ is still within the EM current limit $I_{EMS}(W_{612})$ of the output pin 612 of the NAND gate 94. In addition, the toggle rate of the NAND gate 94 in the chip design is the rate at which the output Out_3 changes with respect to the clock signal CLK. In the example in FIG. 12, the output Out_3 changes from "0" to "1" or from "1" to "0" every 4 clock cycles. Therefore, the toggle rate of the NAND gate 94 is 25%. Similar to the frequency of operation, the higher the toggle rate of the NAND gate 94 is, the higher the RMS current $I_3(C_{L3})$ is. Correspondingly, the maximum EM loading capacitance constraint is changed. In some embodiments, the cell characterization stage 104 is performed after the IC design stage 152, and therefore the simulations for determining the maximum EM loading capacitance constraint can be performed using the frequency of operation and the toggle rate available after the pre-layout simulation. In

other embodiments, the cell characterization stage 104 is performed prior to the IC design stage 152. Therefore, the simulations for determining the maximum EM loading capacitance constraint are performed using default input settings. After the frequency of operation and the toggle rate are available from the pre-layout simulation, the maximum EM loading capacitance constraint is scaled accordingly.

In the embodiments described with reference to FIG. 2, the layout constraint-determining module 224 generates the layout constraint of the interconnect coupled to the output pin of the cell based on the cell netlist in the standard cell library 212, the cell EMS determined by the cell EMS-determining module 222 and the input settings 214 containing the worst case EM input vector. In the embodiments described with reference to FIG. 3, in operation 36, the set of geometric constraints of the interconnect to be coupled to the output pin of the cell in the design layout is determined in view of the EMS of the output pin of the cell. FIG. 13 is a flow diagram of another method performed by the layout constraint-determining module 224 in FIG. 2 or a method performed in the operation 36 in FIG. 3 for determining the set of geometric constraints of the interconnect in accordance with some embodiments. In operation 362, with respect to a wire width of the interconnect, a relationship between wire lengths of the interconnects and output behaviors of the cell is obtained. In operation 364, an EMS of the interconnect is determined based on the wire width of the interconnect. In operation 366, a wire length constraint of the interconnect is determined by identifying, in the relationship between the wire lengths and the output behaviors of the cell, a wire length that corresponds to an output behavior causing the worse of the EMS of the interconnect and the EMS of the output pin of the cell. In operation 368, if a wire width constraint of any wire width is not determined, then the method in FIG. 13 loops back to the operation 362; otherwise, the operation 38 in FIG. 3 will be performed next.

FIG. 14 is a schematic diagram illustrating wire length constraints for interconnects of different wire widths under the EMS of the cell and the EMSes of the interconnects, respectively, in accordance to some embodiments. In operation 362 in FIG. 13, with respect to a wire width $1w$, $2w$ or $3w$ of the interconnect, a relationship between wire lengths of the interconnect and output behaviors such as peak output currents I_{cell_peak} or RMS output currents I_{cell_RMS} of the cell is obtained. In some embodiments, for generating the relationship between the wire lengths of the interconnect and the output behaviors of the cell, a layout including the cell layout such as the cell layout NAND64 of the 4xNAND gate in FIG. 6 and the interconnect with a wire width $1w$, $2w$ or $3w$, and a wire length coupled to the output pin 612 of the cell layout NAND64 is formed. A physical netlist of the layout containing the cell layout NAND64 and the interconnect is generated. By applying the worst case EM input vector described with reference to FIG. 8C to the inputs of the 4xNAND gate in the physical netlist, a peak output current I_{cell_peak} or an RMS output current I_{cell_RMS} of the 4xNAND gate is obtained. Similar operations are performed for other wire lengths until a relationship of the wire lengths and the peak output current I_{cell_peak} or the RMS output current I_{cell_RMS} for the wire width $1w$, $2w$ or $3w$ is obtained.

Referring still to FIG. 14, in operation 364 in FIG. 13, an EM current limit I_{1w_EMS} , I_{2w_EMS} or I_{3w_EMS} of the interconnect is determined based on the wire width $1w$, $2w$ or $3w$ of the interconnect. As described with reference to FIG. 7A, the EM current limit I_{1w_EMS} , I_{2w_EMS} or I_{3w_EMS} of the

interconnect can be obtained by applying the wire width $1w$, $2w$ or $3w$ of the interconnect to the corresponding EM design rule.

Then, in operation 366 in FIG. 13, a wire length constraint of the interconnect is determined by identifying, in the relationship between the wire lengths and the output current I_{cell_peak} or I_{cell_RMS} of the $4\times$ NAND gate for the wire width $1w$, $2w$ or $3w$, a wire length $L_{cell_1w_max}^{cell}$, $L_{cell_2w_max}^{cell}$ or $L_{cell_3w_max}^{cell}$ that corresponds to an output current I_{cell_peak} or I_{cell_RMS} causing the worse of the EM current limit I_{1w_EMS} , I_{2w_EMS} or I_{3w_EMS} of the interconnect and the EM current limit I_{cell_EMS} of the output pin 612 of the $4\times$ NAND gate. In the example shown in FIG. 14, for the wire width $1w$, because the EM current limit I_{1w_EMS} of the interconnect is lower than the EM current limit I_{cell_EMS} of the output pin 612 of the $4\times$ NAND gate, the interconnect of the wire width $1w$ is more susceptible to EM than the output pin 612. Therefore, the wire length constraint for the wire width $1w$ is the wire length that $L_{cell_1w_max}^{cell}$ that corresponds to the EM current limit I_{1w_EMS} in the relationship for the wire width $1w$. Similarly, the wire length constraint for the wire width $2w$ is the wire length $L_{cell_2w_max}^{cell}$ that corresponds to the EM current limit I_{2w_EMS} in the relationship for the wire width $2w$. For the wire width $3w$, because the EM current limit I_{3w_EMS} of the interconnect is higher than the EM current limit I_{cell_EMS} of the output pin 612 of the $4\times$ NAND gate, the output pin 612 is more susceptible to EM than the interconnect of the wire width $3w$. As a result, the wire length constraint for the wire width $3w$ is the wire length $L_{cell_3w_max}^{cell}$ that corresponds to the EM current limit I_{cell_EMS} in the relationship for the wire width $3w$.

FIG. 15 is a schematic diagram of the design layout 1500 in the process of placement in accordance with some embodiments. In the embodiments described with reference to FIG. 2, the place-and-route tool 23 performs placement for a design layout 1500 in accordance with the maximum loading capacitance constraints C_{S2_max} , C_{S4_max} and C_{S5_max} obtained from the layout constraint-determining module 224. In the embodiments described with reference to FIG. 4, in operation 42, placement for a design layout 1500 is performed. In operation 44, capacitances and wire lengths of interconnects IC_1 , IC_2 , and IC_3 to be coupled between the output pins of the cells S_2 , S_4 and S_5 and input pins of other cells S_1 and S_4 , S_3 and S_6 , and S_6 in the design layout 1500, respectively, are estimated. The cell S_2 , S_4 , or S_5 drives the other cells S_1 and S_4 , S_3 and S_6 , or S_6 through the interconnect IC_1 , IC_2 or IC_3 . At the placement stage 156 in FIG. 1, interconnects between the cells are not routed yet and therefore, to estimate capacitances and wire lengths of the interconnects, simplified routing is performed. Then, in operation 46, if the maximum loading capacitance constraint C_{S2_max} , C_{S4_max} , or C_{S5_max} of any cell S_2 , S_4 or S_5 is violated, iterative placement for the design layout 1500 is performed in operation 48, and the method 40 loops back to the operation 44 until the maximum loading capacitance constraints C_{S2_max} , C_{S4_max} and C_{S5_max} are satisfied. The loading capacitance of a cell such as the cell S_2 includes both input capacitances of the cells S_1 and S_4 driven by the cell S_2 , and the capacitance of the interconnect IC_1 coupled between the cell S_2 and the cells S_1 and S_4 . Therefore, to satisfy the maximum loading capacitance constraint C_{S2_max} of the cell S_2 , the sum of the input capacitances of the cells S_1 and S_4 , and the capacitance of the interconnect IC_1 needs to be within the constraint C_{S2_max} . During iterative placement, if the maximum loading capacitance constraint C_{S2_max} , C_{S4_max} , or C_{S5_max} of any cell S_2 , S_4 or S_5 is violated, the placement of the cell S_2 , S_4 or S_5 and/or the placement of at least another cell S_1 and S_4 , S_3 and S_6 or S_6 are adjusted.

As described with reference to FIG. 15, each cell S_2 , S_4 or S_5 has the respective maximum loading capacitance constraint C_{S2_max} , C_{S4_max} , or C_{S5_max} . In this way, the capacitive loading of the cell S_2 , S_4 or S_5 can be adjusted in accordance with the respective driving strength of the cell S_2 , S_4 or S_5 , and the respective EMS of the output pin of the cell S_2 , S_4 or S_5 . Therefore, EM violations or performance degradation due to applying a global maximum loading capacitance constraint to cells with different driving strengths are reduced.

FIG. 16 is a schematic diagram of the design layout 1500 in the process of assigning NDRs before routing in accordance with some embodiments. In the embodiments described with reference to FIG. 2, the place-and-route tool 23 performs routing for the design layout 1500 in accordance with the sets of geometric constraints for the interconnects of the cells obtained from the layout constraint-determining module 224, respectively. In the embodiments described with reference to FIG. 4, in operation 50, an NDR of the interconnect IC_1 , IC_2 or IC_3 to be coupled to the output pin of the cell S_2 , S_4 or S_5 in the design layout 1500 is set as a wire width $1w$, $2w$ or $3w$, in the set of geometric constraints W_{IC1} , W_{IC2} or W_{IC3} that has a corresponding wire length constraint $L_{1w_max}^{S2}$, $L_{2w_max}^{S2}$ or $L_{3w_max}^{S2}$, $L_{1w_max}^{S4}$, $L_{2w_max}^{S4}$ or $L_{3w_max}^{S4}$, $L_{1w_max}^{S5}$, $L_{2w_max}^{S5}$ or $L_{3w_max}^{S5}$ that can be satisfied by the estimated wire length L of the interconnect IC_1 , IC_2 or IC_3 . For example, according to the set of geometric constraints W_{IC1} for the interconnect IC_1 , if the estimated wire length L of the interconnect IC_1 is smaller than or equal to $L_{1w_max}^{S2}$, then the wire width of the interconnect IC_1 is set as $1w$. If the estimated wire length L of the interconnect IC_1 is greater than $L_{1w_max}^{S2}$, and is smaller than or equal to $L_{2w_max}^{S2}$, then the wire width of the interconnect IC_1 is set as $2w$. If the estimated wire length L of the interconnect IC_1 is greater than $L_{2w_max}^{S2}$, and is smaller than or equal to $L_{3w_max}^{S2}$, then the wire width of the interconnect IC_1 is set as $3w$. After all the NDRs of the cells S_2 , S_4 and S_5 are set in operation 52, routing for the design layout 1500 is performed based on the NDRs.

As described with reference to FIG. 16, each cell S_2 , S_4 or S_5 has the respective set of geometric constraints W_{IC1} , W_{IC2} , or W_{IC3} for the interconnect IC_1 , IC_2 or IC_3 . In this way, the NDR of the interconnect IC_1 , IC_2 or IC_3 can be assigned in accordance with the respective driving strength of the cell S_2 , S_4 or S_5 , and the wire length L of the interconnect IC_1 , IC_2 or IC_3 . Compared to a case where an NDR of a cell is set according to a toggle rate of the cell irrespective of the driving strength of the cell, a peak EM current violation of the cell with a high driving strength but a low toggle rate is avoided. Also, an excessively large wire width to prevent RMS EM current violation of the cell with a low driving strength but a high toggle rate is prevented.

FIG. 17 is a functional block diagram of an EM-aware layout generation system 170 in accordance with other embodiments. The EM-aware layout generation system 170 includes a cell EM current constraint-determining module 172, a place-and-route tool 1732 and a current-obtaining tool 1734. In some embodiments, the cell EM current constraint-determining module 172 is employed at the cell characterization stage 104 in FIG. 1, and the place-and-route tool 1732 and the current-obtaining tool 1734 are used at the placement stage 156 and the routing stage 158. The cell EMS current constraint-determining module 172 is configured to receive cell layouts in a standard cell library 1712, and determine, for each cell, a respective EM current limit of an output pin of the cell as the EM current constraint. Compared to the EM layout constraint-generating tool 22 in FIG. 2, the cell EM current constraint-determining module 172 applies the respective EM current limit of each cells, to the place-and-route tool 173

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as a layout constraint that affect a geometry of an interconnect that will be coupled to the cell in a design layout. The place-and-route tool **1732** is configured to receive a gate-level netlist **1716** of a chip design, a floor plan of the design layout **1718**, the cell layouts in the standard cell library **1712**, and the EM current constraints from the cell EM current constraint-determining module **172**, and generate a placement in the design layout **1718**. Simplified routing is also performed on the design layout **1718**. The current-obtaining tool **1734** receives the placed design layout **1718**, and the input settings **1714**, extracts a physical netlist of the design layout **1718**, and calculates a current at each input pin and output pin of each cell. If the current at the output pin of any cell violates the EM current constraint of the cell, the place-and-route tool **1732** performs iterative placement, and the current-obtaining tool **1734** performs netlist extraction and current calculation until the design layout **1718** is clean of EM current constraint violations. The currents at the output pins of the cells in the design layout **1718** clean of the EM current constraint violations are used to determine NDRs for interconnects to be coupled to the output pins of the cells, respectively. Then the place-and-route tool **1732** performs routing in accordance with the NDRs to generate a placed and routed design layout **1742**.

FIG. **18** is a flow diagram of an EM current constraint-generating method **180** in accordance with some embodiments. Compared to the method **30** in FIG. **3**, instead of generating the respective maximum loading capacitance constraint and the respective set of geometric constraints for an interconnect coupled to the output pin of each cell, a respective EM current constraint is generated for each cell. In operation **182**, cell layouts of cells are received. In operation **184**, an EM current constraint of a cell is determined based on a geometry of an output pin of the cell. The EM current constraint is determined similarly to the EM current limit described with reference to FIGS. **7A** and **7B**. In operation **186**, if an EM current constraint of any cell is not determined, the method **180** loops back to the operation **184** to determine the EM current constraint for another cell; otherwise the EM current constraints for the cells are generated and are available for use in an EM-aware placement and routing method **190** in FIG. **19**.

FIG. **19** is a flow diagram of the EM-aware placement and routing method **190** in accordance with other embodiments. Compared to the method **40** in FIG. **4**, the method **190** performs iterative placement until the EM current constraints obtained in FIG. **18** are satisfied and then sets NDRs according to estimated currents at the output pins of the cells, respectively. In operation **191**, placement for a design layout is performed. In operation **193**, currents at the output pins of the cells that are to be coupled to input pins of other cells in the design layout through interconnects are estimated, respectively. In operation **196**, if the EM current constraint of any cell is violated, then the method **190** performs iterative placement for the design layout in operation **198**, and loops back to the operation **193**; otherwise, the method proceeds to the operation **200**. In operation **200**, an NDR of the interconnect to be coupled to the output pin of the cell in the design layout is set using a wire width that can sustain the estimated currents at the output pin of the cell. In operation **202**, if an NDR of an interconnect of any cell is not set, the method **190** loops back to operation **200** to set the NDR for another cell; otherwise, in operation **204**, routing is performed for the design layout based on the NDRs.

FIG. **20** is a schematic diagram of the design layout **2000** in the process of placement in accordance with some embodiments. In the embodiments described with reference to FIG.

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17, the place-and-route tool **1732** generates a placement in the design layout **2000**. Simplified routing is also performed on the design layout **2000**. The current-obtaining tool **1734** receives the design layout **2000**, extracts a physical netlist of the design layout **2000**, and calculates a current I_{11} , I_{31} , I_{41} , I_{61} or I_{62} at each input pin of each cell S_1 , S_3 , S_4 , or S_6 , and a current I_{21} , I_{42} , or I_{51} at a respective output pin of each cell S_2 , S_4 or S_5 . If the current I_{21} , I_{42} , or I_{51} at the output pin of any cell S_2 , S_4 or S_5 violates the EM current constraint I_{S2_EMS} , I_{S4_EMS} , or I_{S5_EMS} of the cell S_2 , S_4 or S_5 , the place-and-route tool **1732** performs iterative placement, and the current-obtaining tool **1734** performs netlist extraction and current calculation until the design layout **2000** is clean of EM current constraint violations. In the embodiments described with reference to FIG. **19**, in operation **193**, currents at I_{21} , I_{42} and I_{51} at the output pins of the cells S_2 , S_4 and S_5 that are to be coupled to input pins of other cells S_1 and S_4 , S_3 and S_6 , and S_6 in the design layout **2000** through interconnects IC_1 , IC_2 and IC_3 , respectively, are estimated respectively. In operation **196**, if the EM current constraint I_{S2_EMS} , I_{S4_EMS} or I_{S5_EMS} of any cell S_2 , S_4 or S_5 is violated, the method **190** performs iterative placement until all the EM current constraints I_{S2_EMS} , I_{S4_EMS} and I_{S5_EMS} are satisfied.

Referring to FIG. **20**, in the embodiments described with reference to FIG. **17**, after the design layout **2000** satisfies all of the EM current constraints I_{S2_EMS} , I_{S4_EMS} , and I_{S5_EMS} , the current I_{21} , I_{42} or I_{51} at the output pin of each cell S_2 , S_4 or S_5 is used to determine a respective NDR for the interconnect IC_1 , IC_2 or IC_3 to be coupled to the output pin of the cell S_2 , S_4 or S_5 . In the embodiments described with reference to FIG. **19**, an NDR of the interconnect IC_1 , IC_2 or IC_3 to be coupled to the output pin of the cell S_2 , S_4 or S_5 in the design layout **2000** is set using a wire width $1w$, $2w$, or $3w$ that can sustain the estimated current I_{21} , I_{42} or I_{51} at the output pin of the cell S_2 , S_4 or S_5 . In some embodiments, current density limits at corresponding temperatures of a wire are defined as EM design rules in a design rule manual. Based the corresponding EM design rule, a predetermined thickness of each segment of the interconnect IC_1 , IC_2 or IC_3 , and the estimated current I_{21} , I_{42} or I_{51} , a wire width for each segment of the interconnect IC_1 , IC_2 or IC_3 can be calculated. Other operations in FIGS. **17** to **19** are similar to those described with references to FIGS. **2** to **16** and are omitted here.

FIG. **21** is a block diagram of a hardware system **2100** for implementing the software system embodiments described with references to FIG. **2** or **17**, and the method embodiments described with reference to FIGS. **3** and **4**, or FIGS. **18** and **19** in accordance with some embodiments. The system **2100** includes at least one processor **2102**, a network interface **2104**, an input and output (I/O) device **2106**, a storage **2108**, a memory **2112**, and a bus **2110**. The bus **2110** couples the network interface **2104**, the I/O device **2106**, the storage **2108** and the memory **2112** to the processor **2102**.

In some embodiments, the memory **2112** comprises a random access memory (RAM) and/or other volatile storage device and/or read only memory (ROM) and/or other non-volatile storage device. The memory **2112** includes a kernel **21124** and user space **21122**, configured to store program instructions to be executed by the processor **2102** and data accessed by the program instructions.

In some embodiments, the network interface **2104** is configured to access program instructions and data accessed by the program instructions stored remotely through a network. The I/O device **2106** includes an input device and an output device configured for enabling user interaction with the system **2100**. The input device comprises, for example, a keyboard, a mouse, etc. The output device comprises, for

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example, a display, a printer, etc. The storage device **2108** is configured for storing program instructions and data accessed by the program instructions. The storage device **2108** comprises, for example, a magnetic disk and an optical disk.

In some embodiments, when executing the program instructions, the processor **2102** is configured to as the software system **20** or **170** described with reference to FIG. **2** or **17** and perform the methods **30** and **40**, or **180** and **190** described with reference to FIGS. **3** and **4** or FIGS. **18** and **19**.

In some embodiments, the program instructions are stored in a non-transitory computer readable recording medium such as one or more optical disks, hard disks and non-volatile memory devices.

Some embodiments have one or a combination of the following features and/or advantages. In some embodiments, to perform EM-aware placement and/or routing for a design layout, each cell has a respective constraint that affects a geometry of an interconnect coupled to the output pin of the cell. The constraint is determined based on a geometry of the output pin of the cell. In some embodiments, the constraint is a maximum loading capacitance constraint. By applying the respective maximum loading capacitance to each cell, a respective driving strength of the cell is considered, and an EM violation caused by an inappropriately low global maximum loading capacitance constraint to a high drive cell, and a timing violation caused by an inadequately high global maximum loading capacitance constraint to a low drive cell are prevented. In some embodiments, the constraint is a set of geometric constraints of the interconnect to be coupled to the output pin of the cell. By applying the respective set of geometric constraints for the interconnect coupled to each cell, a respective driving strength of the cell is considered, and an EM violation caused by assigning a small wire width to a high drive cell with a low toggle rate, and inefficiency resulted from assigning an excessively large wire width to a low drive cell with a high toggle rate are prevented. In other embodiments, the constraint is an EM current constraint at the output pin of the cell. Similarly, by applying the respective EM current constraint at the output pin of each cell, the EM current constraint for the cell is more adequate considering the driving strength and the geometry of the output pin of the cell. Further, because the constraint is determined considering the geometry of the output pin of the cell, a situation where an EM violation occurs in the output pin instead of at the interconnect coupled to the output pin due to ignoring the EMS of the output pin is avoided.

In some embodiments, in a method performed by at least one processor, cell layouts of a plurality of cells are received by the at least one processor. For each cell, a respective constraint that affects a geometry of an interconnect to be coupled to an output pin of the cell in a design layout is determined by the at least one processor based on a geometry of the output pin of the cell in the cell layout.

In some embodiments, a system includes at least one processor configured to execute program instructions which configure the at least one processor as a layout constraint-generating tool, and at least one memory configured to store the program instructions. The layout constraint-generating tool is configured to receive cell layouts of a plurality of cells, and determine, for each cell, a respective constraint that affects a geometry of an interconnect to be coupled to an output pin of the cell in a design layout based on a geometry of the output pin of the cell in the cell layout.

In some embodiments, in a method performed by at least one processor, cell layouts of a plurality of cells are received by the at least one processor. For each cell and with respect to each different first geometric characteristic of an interconnect

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to be coupled to an output pin of the cell in the cell layout, a respective relationship between second geometric characteristics of the interconnect and output behaviors of the cell is obtained by the at least one processor. An electromigration susceptibility (EMS) of the interconnect is determined based on the first geometric characteristic of the interconnect by the at least one processor. Further, a geometric constraint of the interconnect is determined using a second geometric characteristic in the relationship by the at least one processor. The second geometric characteristic corresponds to an output behavior causing the EMS of the interconnect.

The foregoing outlines features of several embodiments so that those skilled in the art may better understand the aspects of the present disclosure. Those skilled in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions, and alterations herein without departing from the spirit and scope of the present disclosure.

What is claimed is:

1. A method, performed by at least one processor, comprising:

receiving, by the at least one processor, cell layouts of a plurality of cells; and

for each cell of the plurality of cells and with respect to each first geometric characteristic of a plurality of first geometric characteristics considered for a first interconnect coupled to an output pin of the cell in the cell layout, obtaining, by the at least one processor, a respective relationship of a plurality of pairs of second geometric characteristic and output behaviors, each second geometric characteristic and each output behavior of the plurality of pairs of second geometric characteristic and output behavior being considered for the first interconnect and being of the cell, respectively, and the first geometric characteristic being orthogonal to each second geometric characteristic of the plurality of pairs of second geometric characteristic and output behavior;

determining, by the at least one processor, respective electromigration susceptibility (EMS) of the first interconnect having the first geometric characteristic; and

determining, by the at least one processor, a respective geometric constraint of the first interconnect using a first pair of second geometric characteristic and output behavior in the respective relationship, the output behavior in the first pair of second geometric characteristic and output behavior causing the respective EMS of the first interconnect.

2. The method of claim 1, wherein,

the method further comprises:

for each cell of the plurality of cells, determining a respective EMS of an output pin of the cell based on a geometric characteristic of the output pin of the cell in the cell layout; and

for each cell of the plurality of cells and with respect to each first geometric characteristic of the plurality of first geometric characteristics considered for the first interconnect coupled to the output pin of the cell in the cell layout,

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the respective geometric constraint of the first interconnect is determined using the first pair of second geometric characteristic and output behavior in the respective relationship,

the output behavior in the first pair of second geometric characteristic and the output behavior causing the worse of the respective EMS of the the first interconnect having the first geometric characteristic and the respective EMS of the output pin of the cell.

3. The method of claim 1, wherein

the respective EMS of the first interconnect having the first geometric characteristic is reflected by a current limit calculated by applying the first geometric characteristic of the first interconnect to an EM design rule; and each output behavior in the plurality of pairs of second geometric characteristic and output behavior is an output current.

4. The method of claim 1, further comprising:

placing a first cell in the plurality of cells and a second cell in the plurality of cells in the design layout; obtaining a third geometric characteristic of a second interconnect coupling the output pin of the first cell to an input pin of the second cell;

selecting a fourth geometric characteristic of the second interconnect from the plurality of first geometric characteristics such that the third geometric characteristic of the second interconnect does not exceed the geometric constraint corresponding to the first cell and the fourth geometric characteristic; and routing the second interconnect based on the selected fourth geometric characteristic.

5. The method of claim 1, further comprising:

for each cell of the plurality of cells, determining a respective electrical constraint using an EMS of the output pin of the cell, the electrical constraint being used for compared with an electrical characteristic of a second interconnect coupled to the output pin of the cell during generation of a design layout, the electrical characteristic of the second interconnect being corresponding to a third geometric characteristic of the second interconnect, and the third geometric characteristic having the same direction as each second geometric characteristic in the respective relationship of each first geometric characteristic of the plurality of first geometric characteristics.

6. The method of claim 5, wherein

the electrical constraint is a loading capacitance constraint.

7. The method of claim 5, wherein

the electrical constraint is an output current constraint.

8. The method of claim 5, wherein for each cell of the plurality of cells, determining the respective electrical constraint comprises:

simulating a plurality of output currents of the cell with respect to a first input vector and a range of electrical characteristics, respectively; and

determining a first electrical characteristic in the range of electrical characteristics that corresponds to a first output current in the plurality of output currents reflecting the EMS of the output pin of the cell as the electrical constraint,

the first input vector being selected from a plurality of input vectors that cause different transitions in a plurality of output voltages of the cell, respectively, and

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the transition caused by the first input vector resulting in the first output current.

9. The method of claim 5, further comprising:

placing a first cell in the plurality of cells and a second cell in the plurality of cells in the design layout; and

performing at least one of a first set of operations and a second set of operations:

a first set of operations comprising:

obtaining an electrical characteristic of a first interconnect coupling the output pin of the first cell to an input pin of the second cell; and

adjusting placement of the first cell and/or the second cell in the design layout until the electrical characteristic of the first interconnect satisfy the electrical constraint corresponding to the first cell; and

a second set of operations comprising:

obtaining a third geometric characteristic of the first interconnect;

selecting a fourth geometric characteristic of the first interconnect from the plurality of first geometric characteristics such that the third geometric characteristic of the first interconnect does not exceed the geometric constraint corresponding to the first cell and the fourth geometric characteristic; and routing the first interconnect based on the selected fourth geometric characteristic.

10. A system, comprising:

at least one processor, configured to execute program instructions which configure the at least one processor as a layout constraint-generating tool comprising:

a layout constraint-determining module configured:

for each cell of the plurality of cells received by the layout constraint-generating tool and with respect to each first geometric characteristic of a plurality of first geometric characteristics considered for a first interconnect coupled to an output pin of the cell in the cell layout,

to obtain a respective relationship of a plurality of pairs of second geometric characteristic and output behavior,

each second geometric characteristic and each output behavior of the plurality of pairs of second geometric characteristic and output behavior being considered for the first interconnect and being of the cell, respectively, and the first geometric characteristic being orthogonal to each second geometric characteristic of the plurality of pairs of second geometric characteristic and output behavior;

to determine a respective electromigration susceptibility (EMS) of the first interconnect having first geometric characteristic; and

to determine a respective geometric constraint of the first interconnect using a first pair of second geometric characteristic and output behavior in the respective relationship, the output behavior in the first pair of second geometric characteristic and the output behavior causing the respective EMS of the first interconnect; and

at least one memory configured to store the program instructions.

11. The system of claim 10, wherein

the layout constraint-generating tool further comprises:

a cell electromigration susceptibility (EMS)-determining module configured

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for each cell of the plurality of cells, to determine a respective EMS of an output pin of the cell based on a geometric characteristic of the output pin of the cell in the cell layout; and

for each cell of the plurality of cells and with respect to each first geometric characteristic of the plurality of first geometric characteristics considered for the first interconnect coupled to the output pin of the cell in the cell layout,

the respective geometric constraint of the first interconnect is determined by the layout constraint-determining module using the first pair of second geometric characteristic and output behavior in the respective relationship,

the output behavior in the first pair of second geometric characteristic and the output behavior causing the worse of the respective EMS of the first interconnect having the first geometric characteristic and the respective EMS of the output pin of the cell.

12. The system of claim **10**, wherein the respective EMS of the first interconnect having the first geometric characteristic is reflected by a current limit calculated by applying the first geometric characteristic of the first interconnect to an EM design rule; and each output behavior in the plurality of pairs of second geometric characteristic and output behavior is an output current.

13. The system of claim **10**, further comprising: a place-and-route tool configured to:

place a first cell in the plurality of cells and a second cell in the plurality of cells in the design layout;

obtain a third geometric characteristic of a second interconnect coupling the output pin of the first cell to an input pin of the second cell;

select a fourth geometric characteristic of the second interconnect from the plurality of first geometric characteristics such that the third geometric characteristic of the second interconnect does not exceed the geometric constraint corresponding to the first cell and the fourth geometric characteristic; and

route the second interconnect based on the selected fourth geometric characteristic.

14. The system of claim **10**, wherein the layout constraint-determining module is further configured:

for each cell of the plurality of cells, to determine a respective electrical constraint using an EMS of the output pin of the cell,

the electrical constraint being used for compared with an electrical characteristic of a second interconnect coupled to the output pin of the cell during generation of a design layout,

the electrical characteristic of the second interconnect being corresponding to a third geometric characteristic of the second interconnect, and

the third geometric characteristic having the same direction as each second geometric characteristic in the respective relationship of each first geometric characteristic of the plurality of first geometric characteristics.

15. The system of claim **14**, wherein the electrical constraint is a loading capacitance constraint.

16. The system of claim **14**, wherein the electrical constraint is an output current constraint.

17. The system of claim **14**, the layout constraint-determining module determines the respective electrical constraint by performing at least one operation comprising:

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simulating a plurality of output currents of the cell with respect to a first input vector and a range of electrical characteristics, respectively; and

determining a first electrical characteristic in the range of electrical characteristics that corresponds to a first output current in the plurality of output currents reflecting the EMS of the output pin of the cell as the electrical constraint,

the first input vector being selected from a plurality of input vectors that cause different transitions in a plurality of output voltages of the cell, respectively, and the transition caused by the first input vector resulting in the first output current.

18. The system of claim **14**, further comprising: a place-and-route tool configured to:

place a first cell in the plurality of cells and a second cell in the plurality of cells in the design layout; and

perform at least one of a first set of operations and a second set of operations:

a first set of operations comprising:

obtaining an electrical characteristic of a first interconnect coupling the output pin of the first cell to an input pin of the second cell; and

adjusting placement of the first cell and/or the second cell in the design layout until the electrical characteristic of the first interconnect satisfy the electrical constraint corresponding to first cell; and

a second set of operations comprising:

obtaining a third geometric characteristic of the first interconnect;

selecting a fourth geometric characteristic of the first interconnect from the plurality of first geometric characteristics such that the third geometric characteristic of the first interconnect does not exceed the geometric constraint corresponding to the first cell and the fourth geometric characteristic; and

routing the first interconnect based on the selected fourth geometric characteristic.

19. A method, performed by at least one processor, comprising:

placing, by the at least one processor, a first cell and a second cell in a design layout;

obtaining, by the at least one processor, an electrical characteristic of a first interconnect coupling an output pin of the first cell to an input pin of the second cell;

adjusting, by the at least one processor, placement of the first cell and/or the second cell in the design layout until the electrical characteristic of the first interconnect satisfy an electrical constraint corresponding to the first cell,

the electrical constraint determined using an electromigration susceptibility (EMS) of the output pin of the first cell; and

obtaining, by the at least one processor, a first geometric characteristic of the first interconnect having the electrical characteristic satisfying the electrical constraint;

selecting, by the at least one processor, a second geometric characteristic of the first interconnect so that the first geometric characteristic of the first interconnect is within a geometric constraint,

the first geometric characteristic being orthogonal to the second geometric characteristic, and

the geometric constraint being determined based on the EMS of the first interconnect having the second geometric characteristic; and

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routing, by the at least one processor, the first interconnect based on the selected second geometric characteristic of the first interconnect.

20. The method of claim **19**, wherein the geometric constraint is determined based on the worse of the EMS of the first interconnect having the second geometric characteristic and the EMS of the output pin of the first cell. 5

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